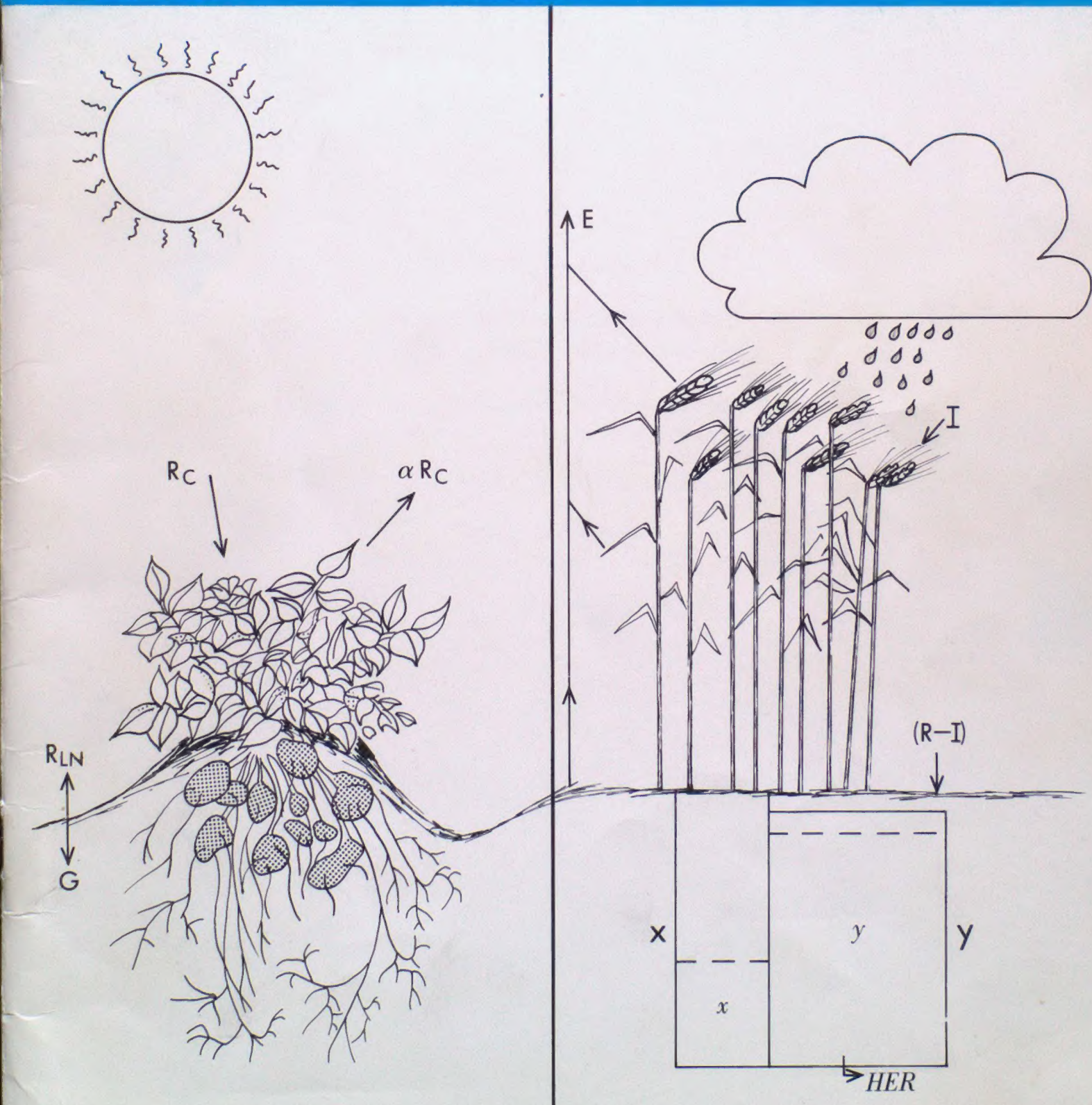
Hydrological Memorandum No. 45

# The Meteorological Office Rainfall and Evaporation Calculation System MORECS (July 1981)



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Hydrological Memorandum No. 45

# The Meteorological Office rainfall and evaporation calculation system: MORECS (July 1981)

by N. Thompson, I.A. Barrie and M. Ayles

Met O 8 (Hydrometeorological Services)
1981

CONTENTS


| | | Page |
|---|---|---|
| 1. | Introduction | 1 |
| 2. | Purpose of MORECS | 2 |
| 3. | Outline of MORECS | 3 |
| 4. | Detailed description of the system | 3 |
| 4.1 | Data collection, averaging and interpolation | 3 |
| 4.1.1 | Data collection: the network of stations and form of data storage | 3 |
| 4.1.2 | Method of averaging data | 3 |
| 4.1.3 | Interpolation of daily average station data to MORECS square estimates | 10 |
| 4.2 | Data analysis to obtain evaporative demand over each grid square | 11 |
| 4.2.1 | Introduction | 11 |
| 4.2.2 | The basic calculation of evapotranspiration: the Penman - Monteith equation | 12 |
| 4.2.2.1 | Available energy: short and long - wave radiation, the effects of cloud, soil heat flux | 15 |
| 4.2.2.2 | Aerodynamic resistance | 19 |
| 4.2.2.3 | Surface resistance when soil moisture is not limiting | 23 |

| | | Page |
|---|---|---|
| 4.3 | Calculation of actual evaporation using a soil moisture extraction model | 27 |
| 4.3.1 | Introduction | 27 |
| 4.3.2 | Relationship between surface resistance and soil moisture deficit | 28 |
| 4.3.3 | Available soil moisture for different crops | 30 |
| 4.4 | Calculation of water balance and excess rainfall | 31 |
| 4.4.1 | Treatment of intercepted water, including condensation | 31 |
| 4.4.2 | Soil moisture deficit and excess rainfall | 32 |
| 4.4.3 | Calculation of real land use values of PE, AE, SMD and HER | 33 |
| 4.5 | MORECS outputs | 34 |
| 4.6 | Comparisons between MORECS outputs and neutron probe data | 34 |
| Acknowledgements | | 36 |
| References | | 37 |
| Annex A: | Dates assumed for crop development | 40 |
| Annex B: | Estimates of percentage of land use types in each MORECS square | 51 |

Page

Annex C: Examples of MORECS outputs 58

Annex D: Comparison of MORECS and neutron probe data 62

Annex E: Summary of changes to MORECS since its introduction in 1978 72

# THE METEOROLOGICAL OFFICE RAINFALL AND EVAPORATION CALCULATION SYSTEM : MORECS (JULY 1981)

by N Thompson, I A Barrie and M Ayles

## 1. INTRODUCTION

MORECS (an acronym for Meteorological Office Rainfall and Evaporation Calculation System) was introduced in 1978 as an eventual replacement for the Estimated Soil Moisture Deficit (ESMD) bulletin first issued by the Office about 15 years earlier. MORECS has undergone a number of changes since its introduction and was extensively revised in the winter of 1980/81, taking account of lessons learnt in the first years of operation of the system. It is expected to run without major changes in the foreseeable future so it is appropriate to provide now, for users and others interested, an extended description of the current version of the scheme. The description appears in the remaining sections of this Memorandum, and is sufficiently detailed to allow the reader to construct a similar scheme to run on his own computer. Listings of MORECS's present computer program are not provided in this Memorandum, in part for commerical reasons, but also because the data bases which the operational version of MORECS requires are peculiar to the Meteorological Office computer system at Bracknell.

## 2. PURPOSE OF MORECS

MORECS has been designed to provide estimates of weekly and monthly evaporation and soil moisture deficit in the form of averages over 40 x 40 km grid squares each superimposed over Great Britain, using daily synoptic weather data as its inputs. The outputs assist hydrologists and agriculturalists in a variety of ways; for example in the assessment of catchment water balance and river flow, leaching of nutrients, and short-term irrigation requirements. A specific requirement is for this information to be available to the user as soon as possible after calculation.

## 3. OUTLINE OF MORECS

The system has five main components (Table 3.1).

Table 3.1 The components of MORECS

| | |
|---|---|
| 1. | Data collection, interpolation and averaging |
| 2. | Data analysis to obtain evaporative demand over each grid square |
| 3. | Calculation of actual evaporation using a soil moisture extraction model |
| 4. | Calculation of water balance and excess rainfall |
| 5. | Data output |

The first is the daily extraction from the Synoptic Data Bank at Bracknell of values of meteorological variables which are sometimes called the Penman variables (sunshine, temperature, vapour pressure, wind speed), and rainfall; objective interpolation is then used to obtain grid-square average values of each variable. The next step is the calculation of daily potential evapotranspiration (PE) for each grid square for a range of surface covers from bare soil to forest, using a modified form of the Penman-Monteith combination equation. In the third part of MORECS the PE estimates are converted to estimates of actual evaporation (AE), by progressively reducing the rate of water loss from the potential value to zero as the available soil moisture decrease from 60% of its maximum value to zero. These calculations are made for soils with high, medium and low available water. The next part calculates the daily water balance under the various types of cropped surfaces, and also under the average land use for each square, in this

latter case using the relative proportions of the various surfaces in each grid-square. The final stage is the production of computer-drawn maps showing the grid-square weekly averages of the Penman variables, and also PE, AE, soil moisture deficit (SMD) and excess rainfall (HER, the hydrologically effective rainfall ie run off and aquifer recharge) for grass and real land use. Printouts are also produced showing the same quantities for the individual surface types. Distribution of output is usually by post, but there are limited issues via Telex, facsimile and Prestel.

## 4. DETAILED DESCRIPTION OF THE SYSTEM

### 4.1 Data collection, averaging and interpolation

#### 4.1.1 Data collection: the network of stations and form of data storage

The network of stations supplying synoptic data which are used by MORECS is shown in Figure 1, with a list of the required meteorological variables which they report given in Table 4.1.1. Rainfall and sunshine are reported directly as daily totals. The other three variables are usually reported several times each day, though a few stations make observations only once daily, at 0900, when 24-hour maximum and minimum temperatures, and 0900 vapour pressure are recorded. All these data are available at Bracknell almost immediately after 0900 GMT and are stored in the Synoptic Data Bank (SDB) there.

#### 4.1.2 Method of averaging data

Daily mean values of air temperature for each station are calculated by averaging observations at 03, 09, 15 and 21GMT. Where any of these observations are missing, the daily mean is taken as the average of daily maximum and minimum temperature. Vapour pressure shows relatively small diurnal variations on average (Barrie and Wylie 1980) and is obtained either by averaging observations (at 03, 09, 15 and 21Z) when more than one of these is taken each day, or from the single 0900 value. The daily mean wind speed is calculated as the average of those taken at any of the hours 03, 09, 15 and 21Z observations: the station is used even when only a single observation is available in the 24-hour period. The calculation of daily averages is done each day and the results stored for use in the interpolation routines described below.

Figure 1
Synoptic stations used by MORECS,
17 September 1981

Table 4.1.1

MORECS synoptic stations

| STATION | WMO NO | METEOROLOGICAL VARIABLES REPORTED | | | | |
|---|---|---|---|---|---|---|
| | | RAIN | SUN | TEMP | WIND | VP |
| COLLAFIRTH HILL | 004 | ✓ | | ✓ | ✓ | ✓ |
| LERWICK | 005 | ✓ | ✓ | ✓ | ✓ | ✓ |
| FAIR ISLE | 008 | ✓ | ✓ | ✓ | ✓ | ✓ |
| KIRKWALL | 017 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BENBECULA | 022 | ✓ | ✓ | ✓ | ✓ | ✓ |
| STORNOWAY | 026 | ✓ | ✓ | ✓ | ✓ | ✓ |
| PRABOST | 027 | ✓ | ✓ | ✓ | | |
| NEIST POINT | 028 | ✓ | | ✓ | ✓ | ✓ |
| ARDNAMURCHAN | 029 | ✓ | | ✓ | | |
| DIABAIG | 033 | ✓ | | ✓ | ✓ | ✓ |
| FORT WILLIAM | 038 | ✓ | | ✓ | | |
| CAPE WRATH | 049 | ✓ | ✓ | ✓ | ✓ | ✓ |
| KINLOSS | 066 | ✓ | ✓ | ✓ | ✓ | ✓ |
| LOSSIEMOUTH | 068 | ✓ | | ✓ | ✓ | ✓ |
| GLENLIVET | 070 | ✓ | ✓ | ✓ | | ✓ |
| WICK | 075 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ABERDEEN/DYCE | 091 | ✓ | ✓ | ✓ | ✓ | ✓ |
| FRASERBURGH | 093 | ✓ | | ✓ | ✓ | ✓ |
| TIREE | 100 | ✓ | ✓ | ✓ | ✓ | ✓ |
| RHUVAAL | 106 | ✓ | | ✓ | ✓ | ✓ |
| DHU LOCH | 107 | ✓ | | ✓ | | |
| MACHRIHANISH | 111 | ✓ | ✓ | ✓ | ✓ | ✓ |
| KILDONAN | 121 | ✓ | ✓ | ✓ | | |
| MULL OF GALLOWAY | 131 | ✓ | | ✓ | ✓ | ✓ |
| SLOY | 133 | | | ✓ | | |
| PRESTWICK | 135 | ✓ | ✓ | ✓ | ✓ | ✓ |
| WHITHORN | 137 | ✓ | ✓ | ✓ | | |
| ABBOTSINCH | 140 | ✓ | ✓ | ✓ | ✓ | ✓ |
| GLENLEE | 147 | ✓ | | ✓ | | |
| CRAWFORDJOHN | 150 | ✓ | | ✓ | | |

MORECS synoptic stations

| STATION | WMO NO | METEOROLOGICAL VARIABLES REPORTED | | | | |
|---|---|---|---|---|---|---|
| | | RAIN | SUN | TEMP | WIND | VP |
| SALSBURGH | 152 | ✓ | | ✓ | | |
| DUMFRIES/DRUNGANS | 154 | ✓ | | ✓ | | |
| PITREAVIE | 156 | ✓ | | ✓ | | |
| PERTH | 157 | ✓ | | ✓ | | |
| TURNHOUSE | 160 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ESKDALEMUIR | 162 | ✓ | ✓ | ✓ | ✓ | ✓ |
| GALASHIELS | 168 | | | | | |
| LEUCHARS | 171 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ST ABBS HEAD | 185 | ✓ | | ✓ | | ✓ |
| RONALDSWAY | 204 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ST BEES HEAD | 211 | ✓ | | | | |
| ESKMEALS | 213 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ASPATRIA | 215 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CARLISLE | 222 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BOULMER | 240 | ✓ | ✓ | ✓ | ✓ | ✓ |
| LEEMING | 257 | ✓ | ✓ | ✓ | ✓ | ✓ |
| TYNEMOUTH | 262 | ✓ | ✓ | ✓ | ✓ | ✓ |
| FYLINGDALES | 281 | ✓ | | ✓ | | |
| WHITBY | 282 | ✓ | | ✓ | ✓ | ✓ |
| VALLEY | 302 | ✓ | ✓ | ✓ | ✓ | ✓ |
| SQUIRES GATE | 318 | ✓ | ✓ | ✓ | ✓ | ✓ |
| AUGHTON MET | 322 | ✓ | ✓ | ✓ | ✓ | ✓ |
| RINGWAY | 334 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CELLARHEAD | 338 | ✓ | | ✓ | ✓ | ✓ |
| HOLME MOSS | 342 | ✓ | | ✓ | | |
| WILSDEN | 344 | ✓ | | ✓ | ✓ | ✓ |
| EMLEY MOOR | 345 | ✓ | | ✓ | | |
| WATNALL | 354 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CHURCH FENTON | 355 | ✓ | | ✓ | | |
| FINNINGLEY | 360 | ✓ | ✓ | ✓ | ✓ | ✓ |
| WADDINGTON | 377 | ✓ | ✓ | ✓ | ✓ | ✓ |

MORECS synoptic stations

| STATION | WMO NO | METEOROLOGICAL VARIABLES REPORTED | | | | |
|---|---|---|---|---|---|---|
| | | RAIN | SUN | TEMP | WIND | VP |
| CRANWELL | 379 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BINBROOK | 388 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CONINGSBY | 391 | ✓ | | ✓ | ✓ | ✓ |
| BARDSEY ISLAND | 400 | ✓ | | ✓ | ✓ | ✓ |
| TRAWSFYNYDD | 406 | ✓ | | ✓ | ✓ | ✓ |
| SHAWBURY | 414 | ✓ | ✓ | ✓ | ✓ | ✓ |
| WITTERING | 462 | ✓ | | ✓ | ✓ | ✓ |
| MARHAM | 482 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CROMER | 494 | ✓ | | | ✓ | ✓ |
| COLTISHALL | 495 | ✓ | | ✓ | ✓ | ✓ |
| HEMSBY | 496 | ✓ | ✓ | ✓ | ✓ | ✓ |
| GORLESTON | 497 | ✓ | ✓ | ✓ | | |
| ABERPORTH | 502 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CENARTH | 504 | | | | | |
| ELMDON | 534 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BEDFORD | 558 | ✓ | ✓ | ✓ | ✓ | ✓ |
| WYTON | 566 | ✓ | | ✓ | ✓ | ✓ |
| HONNINGTON | 586 | ✓ | ✓ | ✓ | ✓ | ✓ |
| WATTISHAM | 590 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BRAWDY | 603 | ✓ | ✓ | ✓ | ✓ | ✓ |
| MILFORD HAVEN | 604 | ✓ | | ✓ | ✓ | ✓ |
| BRYNAMMAN | 611 | ✓ | | ✓ | | |
| TRECASTLE | 612 | | | ✓ | | |
| CILFYNYDD | 614 | ✓ | | ✓ | ✓ | ✓ |
| GLOUCESTER | 633 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BRIZE NORTON | 649 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BENSON | 658 | ✓ | ✓ | ✓ | ✓ | ✓ |
| STANSTED | 683 | ✓ | ✓ | ✓ | ✓ | ✓ |
| SHOEBURYNESS | 693 | ✓ | ✓ | ✓ | ✓ | ✓ |
| LUNDY | 702 | ✓ | | ✓ | | |

MORECS synoptic stations

| STATION | WMO NO | METEOROLOGICAL VARIABLES REPORTED | | | | |
|---|---|---|---|---|---|---|
| | | RAIN | SUN | TEMP | WIND | VP |
| HARTLAND PT | 703 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CHIVENOR | 707 | ✓ | | ✓ | ✓ | ✓ |
| EXTON | 711 | ✓ | | ✓ | | |
| RHOOSE | 715 | ✓ | ✓ | ✓ | ✓ | ✓ |
| LYNEHAM | 740 | ✓ | ✓ | ✓ | ✓ | ✓ |
| LARKHILL | 743 | | | | | |
| UPAVON | 744 | ✓ | | ✓ | | |
| BOSCOMBE DOWN | 746 | ✓ | ✓ | ✓ | ✓ | ✓ |
| SOUTH FARNBOROUGH | 766 | ✓ | | ✓ | ✓ | ✓ |
| HEATHROW | 772 | ✓ | ✓ | ✓ | ✓ | ✓ |
| GATWICK | 776 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CHARING | 785 | ✓ | | ✓ | | |
| ULCOMBE | 789 | ✓ | ✓ | ✓ | ✓ | ✓ |
| MANSTON | 797 | ✓ | ✓ | ✓ | ✓ | ✓ |
| SCILLY | 804 | ✓ | ✓ | ✓ | ✓ | ✓ |
| GWENNAP HEAD | 806 | ✓ | | ✓ | ✓ | ✓ |
| CAMBOURNE | 808 | ✓ | ✓ | ✓ | ✓ | ✓ |
| CULDROSE | 809 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ST MAWGAN | 817 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BASTREET | 824 | ✓ | ✓ | ✓ | | |
| MOUNT BATTEN | 827 | ✓ | ✓ | ✓ | ✓ | ✓ |
| BURRINGTON | 830 | ✓ | | ✓ | | |
| OKEHAMPTON | 832 | ✓ | | ✓ | | |
| EXETER | 839 | ✓ | ✓ | ✓ | ✓ | ✓ |
| YEOVILTON | 853 | ✓ | | ✓ | ✓ | ✓ |
| PORTLAND BILL | 855 | ✓ | ✓ | ✓ | ✓ | ✓ |
| ANVIL POINT | 860 | ✓ | | ✓ | | |
| HURN | 862 | ✓ | ✓ | ✓ | ✓ | ✓ |
| SOUTHAMPTON WEATHER CENTRE | 865 | ✓ | | | | |
| ST CATHERINE'S POINT | 866 | ✓ | | ✓ | ✓ | ✓ |
| EAST HOATHLY | 877 | ✓ | ✓ | ✓ | | |

## MORECS synoptic stations

| STATION | WMO NO | METEOROLOGICAL VARIABLES REPORTED | | | | |
|---|---|---|---|---|---|---|
| | | RAIN | SUN | TEMP | WIND | VP |
| HERSTMONCEUX | 884 | ✓ | ✓ | ✓ | ✓ | ✓ |
| FAIRLIGHT | 886 | ✓ | | ✓ | ✓ | ✓ |
| Recent additions | | | | | | |
| TARBETNESS | 061 | ✓ | | ✓ | ✓ | ✓ |
| FIFE NESS | 174 | ✓ | | ✓ | ✓ | ✓ |
| MERTHYR TYDFIL | 613 | ✓ | | ✓ | | |
| BRISTOL WEATHER CENTRE | 726 | ✓ | | ✓ | ✓ | ✓ |
| BRACKNELL/BEAUFORT PARK | 763 | ✓ | ✓ | | | |
| Stations received by telex specifically for MORECS | MORECS No. | | | | | |
| LUDLOW | 952 | ✓ | | | | |
| STANSTEAD ABBOTS | 968 | ✓ | | | | |
| COPPER MILLS | 978 | ✓ | | | | |

4.1.3 Interpolation of daily average station data to MORECS square estimates

The station data are first normalised or standardised as follows:

(i) Rainfall is expressed as a percentage of the annual station average.

(ii) Sunshine is converted to percentage of the average daily duration for the month.

(iii) Temperature and vapour pressure are 'reduced' to sea level, using lapse rates of respectively -0.6 deg C/100m and 2.5%/100m.

(iv) The 10 m windspeed is converted to a value appropriate to a standard site using an empirical factor related to the general terrain roughness around the station.

Interpolation to obtain 40 x 40 km square values is now carried out. First the 9 nearest stations to the centre of each square are selected, irrespective of whether they have data, up to a maximum of 100 km from the centre. However, if there is a station within 0.5 km of the centre then its observations are used alone. Otherwise, from the selected 9 stations there are chosen the 6 nearest with data, but with the proviso that there are no more than 2 stations in each octant. If less than 3 stations are found then an inverse distance squared method of interpolation is used, otherwise plane fitting is carried out (Shearman and Salter 1975).

The grid-square values are then obtained. In the case of rainfall this involves conversion of the percentage value to millimetres using average annual rainfall for the square (1941-70). Similarly sunshine is expressed in hours by using the square-average mean daily duration for the month (1941-70). The interpolated temperatures and vapour pressures are adjusted to the mean altitude of each square. Finally the wind speed values are converted to squares estimates by applying a correction which takes into account the average terrain roughness for the square.

Errors involved in the use of these interpolation procedures are unlikely to be large in the case of temperature and humidity which usually show only slow changes with distance after conversion to sea level. Acceptable estimates of wind speed will also be obtained usually. Greater difficulties are experienced with sunshine. The network of sunshine recorders is fairly sparse, even when both synoptic and climatological stations

are considered and so it is difficult to establish representative long-term daily average values of sunshine duration for the month in each square. This is especially so where the square includes much high ground, because of the paucity of upland measuring sites. For these reasons it is likely that square values of sunshine duration will be overestimated for squares with substantial amounts of high ground. Rainfall shows large spatial variation, even over homogeneous terrain, especially during summer. It is possible to establish fairly reliable long-term average annual rainfall for each square using data from the several thousand rainfall stations. This means that in the very long term the estimates of MORECS square rainfall derived from the limited synoptic rainfall data will be satisfactory. In the shorter term though, such estimates can be misleading, and for this reason it is recommended that those who use MORECS outputs for irrigation scheduling should **install their own rain-gauge.**

## 4.2 Data analysis to obtain evaporative demand over each grid square

### 4.2.1 Introduction

Central to MORECS is the scheme used to determine the potential and actual evapotranspiration from the various surfaces which the system considers. Inadequate treatments here are likely to produce systematic errors in calculated evaporation. Corresponding percentage errors in soil moisture deficit will often be larger, since SMD is determined by differences between evaporation and rainfall, with the latter quantities having similar orders of magnitude for much of the year. It is possible to write down physically rigorous equations which will in principle provide very accurate estimates of evaporation. In practice the solution of the equations (to allow for example for the diurnal changes of atmospheric stability) is impossible analytically: the iterative methods which have to be used instead are far too time-consuming for operational use. Simplification is needed therefore and a consequent loss of accuracy. In fact the major errors in a scheme like MORECS arise through shortcomings in the meteorological data-set( § 4.1.1), and difficulties in specifying the magnitude of the necessary crop physiological variables: errors involved in simplifying the treatment of the physical processes can be made negligible by comparison with the others.

MORECS uses a slightly modified version of the Penman-Monteith equation to calculate directly both potential and actual evapotranspiration, in the latter case adjusting the bulk surface resistance according to the magnitude of the soil moisture deficit. Calculations are done separately for the day and night-time periods, with the daily mean values of wind and temperature being adjusted empirically according to which period is being considered (Barrie and Wylie 1980). The improvement in accuracy gained by following this procedure is small, but it has been adopted in anticipation of possible future use of the night-time results for other operational purposes.

4.2.2 The basic calculation of evapotranspiration: the Penman-Monteith equation

The Penman-Monteith equation provides a rational, physically-based means of calculating water loss from any surface. The equation is

$$\lambda E = \frac{\Delta (R_N - G) + \rho c_p (e_s - e)/r_a}{\Delta + \gamma (1 + r_s/r_a)} \qquad (4.1)$$

where $E$ = rate of water loss (Kg $m^{-2} s^{-1}$)

$\Delta$ = rate of change of saturated vapour pressure with temperature (mb $^{o}C^{-1}$)

$R_N$ = net radiation ($Wm^{-2}$) (+ve downwards)

$G$ = soil heat flux ($Wm^{-2}$) (+ve downwards)

$\rho$ = air density (Kg $m^{-3}$) 1·2923 at STP

$c_p$ = specific heat of air at constant pressure (1005 J $Kg^{-1}$)

$e_s$ = saturation vapour pressure at screen temperature (mb)

$e$ = screen vapour pressure (mb)

$\lambda$ = latent heat of vaporisation ( $\simeq$ 2465000 J $Kg^{-1}$)

$\gamma$ = psychromatic constant (= 0.66 for temperatures in deg C and vapour pressures in mb)

$r_s$ = bulk surface resistance ($sm^{-1}$)

$r_a$ = bulk aerodynamic resistance ($sm^{-1}$)

Direct measurements of $R_N$ are not available for use in MORECS and so $R_N$ has to be estimated using empirical formulae (see § 4.2.2.1).

These formulae assume, inter alia, that the effective surface temperature is equal to screen temperature. This introduces errors, but an attempt to correct them may be made by modifying slightly the Penman-Monteith equation along the lines suggested by Monteith (1981). Thus, one may write

$$R_N = R_{NE} + C \qquad (4.2)$$

where $R_{NE} = R_N$ calculated assuming $T_o = T_{SCR}$

$T_o$ = bulk surface temperature

$T_{SCR}$ = screen temperature

$C$ = correction term

$$= \epsilon\sigma((273.1+T_{SCR})^4 - (273.1+T_o)^4) \qquad (4.2)$$

$\epsilon$ = emissivity of surface

$\sigma$ = Stefan's constant ($5.67 \times 10^{-8}$ $Wm^{-2}$ $^oK^{-4}$)

For small values of $T_{SCR} - T_o$ , Eq (4.3) reduces to

$$C \doteq 4\epsilon\sigma (273.1+T_{SCR})^3 (T_{SCR}-T_o)$$

$$= b'(T_{SCR}-T_o) \qquad (4.4)$$

Thus,

$$R_N = R_{NE} + b'(T_{SCR}-T_o) \qquad (4.5)$$

The new combination equation may now be derived. The energy balance at the surface is

$$\lambda E = R_{NE} - G - H - b'(T_o - T_{SCR}) \qquad (4.6)$$

where $H$ = upward flux density of sensible heat from the surface ($Wm^{-2}$)

The resistance equation for this flux density is

$$H = \rho c_p (T_o - T_{SCR})/r_{aH} \qquad (4.7)$$

where $r_{aH}$ = bulk resistance to transfer of sensible heat from its origin at the surface, up to screen height

Similarly

$$E = \rho(q_o - q_{SCR})/(r_s + r_{aE}) \qquad (4.8)$$

where $q_o$ = specific humidity in the substomatal cavities of the surface cover

$\simeq$ saturation specific humidity at bulk surface temperature

$r_s$ = bulk resistance to transfer of water vapour from within the sub-stomatal cavities to (bulk) foliage surface

$r_{aE}$ = bulk resistance to transfer of water vapour from bulk foliage surface up to screen height

Also

$$q_o - q_{scr} = q_o - q_s(T=T_{scr}) + q_s(T=T_{scr}) - q_{scr}$$
$$\simeq \Delta'(T_o - T_{scr}) + \delta q \qquad (4.9)$$

where $\Delta'$ = rate of change of saturation specific humidity with temperature

$\delta q$ = specific humidity deficit at screen height

Thus

$$E = \rho(\Delta'(T_o - T_{scr}) + \delta q)/(r_s + r_{aE}) \qquad (4.10)$$

Now,

$$r_{aE} \simeq r_{aH} = r_a$$

Then, from Equations (4.6) and (4.7)

$$\lambda E = R_{NE} - G - (T_o - T_{scr})(\rho c_p/r_a + b') \qquad (4.11)$$

Eliminating $T_o - T_{scr}$ between (4.10) and (4.11)

$$E(1 + r_s/r_a) = \rho \delta q/r_a + \frac{\Delta'((R_{NE} - G) - \lambda E)}{c_p(1 + b' r_a/\rho c_p)}$$

or,

$$E(c_p(1 + r_s/r_a)(1 + b' r_a/\rho c_p) + \Delta'\lambda) = \rho c_p \delta q (1 + b' r_a/\rho c_p)/r_a + \Delta'(R_{NE} - G)$$

Thus,

$$\lambda E = \frac{\Delta'(R_{NE} - G) + \rho c_p \delta q (1 + b' r_a/\rho c_p)/r_a}{\Delta' + c_p(1 + r_s/r_a)(1 + b' r_a/\rho c_p)/\lambda} \qquad (4.12)$$

Writing this equation in terms of vapour pressure rather than specific humidity leads to

$$\lambda E = \frac{\Delta (R_{NE}-G) + \rho c_p (e_s-e)(1+b'r_a/\rho c_p)/r_a}{\Delta + \gamma (1+r_s/r_a)(1+b'r_a/\rho c_p)} \qquad (4.13)$$

: this is the combination equation used in MORECS

4.2.2.1 Available energy: short and long-wave radiation, the effects of cloud, soil heat flux

The downward daily total of short-wave radiation at the surface ( $R_c$ ) is expressed in terms of the radiation flux density ( $R_A$ ) at the top of the atmosphere using the scheme of Cowley (1978) which involves application of the empirical relation.

$$R_c = R_A(\eta(a+bn/N)+c(1-\eta)) \qquad (W\ hr\ m^{-2}) \qquad (4.14)$$

where

$$R_A = \int_{t_1}^{t_2} S \sin\Theta\, dt$$

$$= \int_{t_1}^{t_2} S\left(\sin\delta\sin\phi - \cos\delta\cos\phi\cos\frac{\pi t}{12}\right) dt$$

$$= S\left((t_2-t_1)\sin\delta\sin\phi + \frac{12}{\pi}\cos\delta\cos\phi\left(\sin\frac{\pi t_1}{12} - \sin\frac{\pi t_2}{12}\right)\right) \qquad (4.15)$$

$\Theta$ = solar elevation

$\delta$ = solar declination

$= 0.41 \cos(2\pi(d-172)/365)$

$d$ = day of year (1 ≡ 1 January)

$\phi$ = latitude

$S$ = solar constant

$= 1360\left(1+0.035\cos(2\pi d/365)\right) \quad (Wm^{-2}) \qquad (4.16)$

(Hughes et al 1977)

$t_1$ = local time of sunrise

$$= \frac{12}{\pi} \arccos(\tan\delta \tan\phi + 0.0145/(\cos\delta\cos\phi)) \quad (4.17)$$

: this expression allows for the refraction ( ~ 34') and sun radius ( ~ 16') so that sunrise occurs when the sun centre is still 50' below the horizon

$t_2$ = local time of sunset
$= 24 - t_1$
$N$ = day length
$= t_2 - t_1$
$= 24 - 2t_1$
$n$ = measured number of hours of bright sunshine
$\eta = 0$ if $n = 0$
$\eta = 1$ if $n > 0$

$a$ and $c$ are independent of season, with respective values of 0.24 and 0.15, varying geographically by about $\pm$ 0.02. $b$ varies both seasonally and geographically, increasing from about 0.50 in winter to 0.55 in summer, with a further geographic variation of around 0.05.

The net shortwave radiation at the surface is

$$R_{NS} = (1-\alpha) R_c \quad (4.18)$$

where $\alpha$ is the albedo of the surface. Values of albedo used in MORECS for different surfaces are shown in Table 4.2.1.

Table 4.2.1 MORECS albedos

| Surface type | Albedo | Surface type | Albedo |
|---|---|---|---|
| Grass | 0.25 | Upland | 0.25 |
| Cereals (Wheat, barley) | 0.25 | Riparian | 0.25 |
| Potatoes (early and maincrop) | 0.25 | Bare rock | 0.12 |
| | | Conifers | 0.12 |
| Sugar beet | 0.25 | Impervious urban | 0.10 |
| Orchards | 0.25 | Water | 0.05 |
| Deciduous trees | 0.17 | Bare soil (dry) | 0.10, 0.20, 0.30[a] |
| | | Bare soil (wet) | 0.05, 0.10, 0.15[a] |

(a) Values refer respectively to soils of high, medium and low available water capacity

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The values in the Table for the various types of vegetation refer to a fully developed crop cover. In the case of an incomplete cover a simple empirical correction to albedo is used:

$$\alpha = \alpha_s + 0.25\,(\alpha_c - \alpha_s)\,\mathfrak{L} \qquad \mathfrak{L} \leq 4) \qquad (4.19)$$
$$= \alpha_c \qquad \mathfrak{L} > 4)$$

where $\alpha_s$ = albedo for bare soil

$\alpha_c$ = albedo for full crop cover

$\mathfrak{L}$ = leaf area index

The incoming long-wave radiation ( $R_{L\downarrow}$ ) is estimated using the technique of Brutsaert (1975). Unlike most other methods, Brutsaert's has a minimum of empiricism, being based on the equations of radiative transfer. The expression he derived for clear skies is

$$R_{L\downarrow} = a'\sigma K_{SCR}^4 \left(e_{SCR}/K_{SCR}\right)^{1/7} \qquad (Wm^{-2}) \qquad (4.20)$$

where $e_{SCR}$ = vapour pressure at screen height

$K_{SCR}$ = screen temperature in deg K

The value of $a'$ is slightly dependent on assumptions about the variations of temperature and vapour pressure with height in the lowest few kilometres of the atmosphere. Brutsaert's treatment suggested a value of about 1.24 but a comparison with experimental data gives a value of around 1.28 which is used in MORECS (Barrie 1981).

Upward long-wave radiation from the surface is (putting $K_{SCR} \simeq K_{SURFACE}$ )

$$R_{L\uparrow} = \epsilon\sigma K_{SCR}^4 \qquad (Wm^{-2}) \qquad (4.21)$$

where the emissivity $\epsilon$ is assumed to be 0.95. The net long-wave radiation for clear skies is then

$$R_{LN} = \epsilon\sigma K_{SCR}^4 \left(1.28\left(e_{SCR}/K_{SCR}\right)^{1/7} - 1\right) \qquad (Wm^{-2}) \qquad (4.22)$$

The effects of cloud on $R_{LN}$ are assumed to be those suggested by Linacre (1968) so that the general expression is

$$R_{LN} = \epsilon\sigma K_{scr}^{4}\left(1.28\left(e_{scr}/K_{scr}\right)^{1/7}-1\right)\left(0.2+0.8n'/N\right) \quad (Wm^{-2}) \qquad (4.23)$$

For daytime calculations $n'$ takes a value equal to the number of hours of bright sunshine. At night the amount of cloud is smaller usually than during the day (Barrie 1980), by about 10% typically, so that $n' \simeq 1.1\,n$ (with a maximum value limited to 1.0).

Following Monteith (1958) the daytime flux density of heat into bare soil is assumed to be

$$G_d = 0.3\,R_{Nd} \qquad (4.24)$$

where $R_{Nd}$ is the average daytime net all-wave radiation flux density, given by

$$R_{Nd} = R_{NL} + (1-\alpha)\,R_c/(t_2-t_1) \qquad (4.25)$$

: the corresponding value for a grass-covered surface is

$$G_d = 0.2\,R_{Nd} \qquad (4.26)$$

and for other crops is

$$G_d = (0.3 - 0.03\,f)\,R_{Nd} \qquad (4.27)$$

The night-time value for $G$ is calculated using a scheme suggested by Wales-Smith and Arnott (1980). They used measurements of soil temperature at Kew with estimated soil thermal capacities to calculate the average monthly heat storage in the soil, and the corresponding average flux density of heat at the soil surface. Values of daily heat storage calculated in this way are given in Table 4.2.2:

Table 4.2.2 Average daily heat storage in soil ( P ) (W hr $m^{-2}$)

| J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -137 | -75 | 30 | 167 | 236 | 252 | 213 | 69 | -85 | -206 | -256 | -206 |

they are assumed to apply over the whole MORECS grid. Thus the average night-time value of $G$ ($Wm^{-2}$) is

$$G_n = \frac{(t_2-t_1)\,G_d - P}{2t_1} \qquad (4.28)$$

Finally, the available energy is calculated from

$$\left.\begin{array}{l}\text{daytime available energy} = R_{Nd} - G_d \\ \text{night-time available energy} = R_{LNn} - G_n\end{array}\right\} \quad (4.29)$$

4.2.2.2 Aerodynamic resistance

The aerodynamic resistances for heat and water vapour transfer are defined by eq (4.7) and (4.8). Experimental evidence shows that they are negligibly different in magnitude. The resistances may also be defined in terms of the vertical eddy diffusion coefficient for heat and water vapour transfer ( $K_{H,E}(z)$ ), thus demonstrating the role of atmospheric turbulence in transferring heat and water vapour away from the surface. In this form the definition is

$$r_{aH} = r_{aV} = r_a = \int_{z_{T,q}}^{z-d} (1/K_{H,E}(z))\, dz \quad (4.30)$$

Here $z_{T,q}$ is the roughness length of the surface for heat and water vapour transfer. Momentum may be transferred to surfaces by pressure forces as well as molecular diffusion and so the roughness length for momentum transfer ( $z_o$ ) is larger than $z_{T,q}$ . Thom (1975) developed this idea and showed that

$$z_{T,q} \simeq 0.2\, z_o \quad (4.31)$$

Typical values for $z_o$ are about $0.1h$ , where $h$ is the crop height, and so $z_{T,q} \simeq 0.02h$ .

In equation (4.30) the upper limit of integration is $z-d$ , rather than $z$ . This acknowledges that the effective mean height at which the heat and water vapour originates is $d+z_{T,q}$ , where $d$ is the zero-plane displacement height: it has a typical value of about $0.6h$ (Monteith 1973). The temperatures and humidities which MORECS uses are measured over short grass at a height of 1.2 m (screen height), for which $d$ can be ignored. The assumption is made that these data will also apply at a height of 1.2 m above the zero-plane of any other surface. Hence the MORECS $r_a$ should be defined by

$$r_a = \int_{z_{T,q}}^{z'-d} (1/K_{H,E}(z))\, dz \quad (4.32)$$

where

$$z' = 1.2 + d \qquad \text{(metres)}$$

In conditions of near-neutral atmospheric stability the variations of wind and temperature with height are logarithmic, and equation (4.32) may be integrated to give (Thom and Oliver 1977).

$$r_a = (1/k^2\, U(z'))\, \ln(1.2/z_o)\, \ln(1.2/z_{T,q}) \qquad (4.33)$$

MORECS assumes that its measured 10 m winds ( $U_m(10)$ ) are equal to the wind speed $U(10+d)$ at $10+d$ metres above the surface underlying the crop, or that wind speeds at 10 m above the zero-plane are the same for different crops. This is a bad approximation over very tall, very rough crop covers (eg conifers) and for these cases, following Oliver (1974), the relation

$$U(10+d) = 0.6\, U_m(10) \qquad (4.34)$$

is used, in a somewhat different treatment outlined at the end of this section. From the logarithmic wind profile it may be shown that

$$U(z')/U(10+d) = \ln(1.2/z_o)/\ln(10/z_o) \qquad (4.35)$$

Using the relation $z_o = 0.1h$ , and equations (4.33), (4.35), and where appropriate (4.34), one may then calculate $r_a$ , noting that eq (4.33) and (4.35) give

$$r_a = (6.25/U(10+d))\, \ln(10/z_o)\, \ln(6/z_o) \qquad (4.36)$$

The treatments described by the foregoing equations are poor approximations over very rough surfaces where the level ( $1.2+d$ ) metres may be well within, rather than above, the foliage. In these cases the upper reference level is taken to be ( $10+d$ ) metres above the ground surface, and the vapour pressure deficit calculated from the screen data is assumed to apply at this height over the forested area. $r_a$ is then given by

$$r_a = (6.25/U(10+d)) \ln(10/z_o) \ln(50/z_o) \quad (4.37)$$

Then, for mature conifers and deciduous trees (in full leaf), for which $z_o \simeq 1$ m,

$$r_a = 56.3 / U(10+d)$$

$$\simeq 94 / U_m(10) \quad (4.38)$$

Use of the neutral forms for $r_a$ (eq (4.36), (4.38)) requires some justification. Thompson (1981) made exact calculations of evapotranspiration using the Penman-Monteith equation with given input values for available energy, vapour pressure deficit, wind speed, surface roughness, temperature and surface resistance, with full allowance for non-neutral stability in calculating $r_a$, and with and without correction to available energy resulting from surface heating: the results were compared with estimates made using the method outlined above, and with estimates obtained using the modified form of Penman's original form for $r_a$ suggested by Thom and Oliver, also with and without allowance for the effects of surface heating on available energy. The method described in detail above gave the best agreement with the exact calculations, and for typical values of the input variables was usually within better than 10% of the exact model. It showed a small overall bias towards underestimation, but this conveniently compensates to some extent for neglect of the available energy used in photosynthesis by the transpiring crop.

The crop heights used by MORECS are shown in Table 4.2.3. Values for annual crops are assumed to vary during the season according to the relation

$$\begin{aligned} h &= h_1 + (h_2 - h_1)(d - d_e)/(d_f - d_e) && d_e < d < d_f \\ &= h_2 && d_f < d < d_h \end{aligned} \quad (4.39)$$

where $h_1, h_2$ are the minimum and maximum heights listed in Table 4.2.3

$d$ = day of year

$d_e$ = (spring-sown crops) assumed emergence date ) Annexe A

= (autumn-sown crops) assumed date of start of spring growth after winter dormancy - Annexe A

$d_f$ = assumed date when crop reaches maximum height

$d_h$ = assumed harvest date

Deciduous trees, including orchard trees, are assumed to foliate, and defoliate, over periods of 40 days, with linear changes of their effective heights over these periods.

Table 4.2.3 Effective crop heights used in MORECS

| Crop | Height (m) | Crop | Height (m) |
|---|---|---|---|
| Grass | 0.15 | Orchards[c] | 0.15, 2.0, 3.0 |
| Spring barley[a] | 0.05 - 0.8 | Conifers | 10.0 |
| Winter wheat[b] | 0.08 - 0.8 | Upland | 0.15 |
| Winter barley[b] | 0.08 - 0.8 | Impervious urban | 10.0 |
| Potatoes[a] | 0.05 - 0.6 | Bare rock | 0.05 |
| Sugar beet[a] | 0.05 - 0.35 | Water | 0.005 |
| Deciduous trees[c] | 0.15, 2.0, 10.0 | Bare soil | 0.05 |

(a) Range of values for spring-sown crops refer to the period emergence to harvest

(b) Range of values for autumn-sown crops refer to the over-winter period, up to harvest

(c) First value is for defoliated trees, the second at leaf emergence, and the third for full leaf

4.2.2.3 Surface resistance when soil moisture is not limiting

Correct specification of surface resistance $r_s$ is crucial to the satisfactory running of MORECS. $r_s$ varies widely with type and age of crop, and with external factors such as soil moisture deficit. It is not possible to include these variations in other than a simple fashion in MORECS, partly to keep the complexity of the computation scheme within bounds, but also because data on many of the physiological responses are at present inadequate. The aim has to be to incorporate a realistic scheme which will account for seasonal changes including variable leaf area index for the main surface types which are considered. For most of these surfaces it is necessary to calculate $r_s$ on a daily basis for both day and night-time, using where appropriate data given in Annexe A.

For seasonal crops the surface will range from bare soil, to moderately or densely foliated. Water may be extracted directly from both the soil and the crop, and the surface resistance has to be calculated taking both these processes into account. The basic scheme follows that suggested by Grant (1975) and uses the expression

$$1/r_s = (1-A)/r_{sc} + A/r_{ss} \qquad (4.40)$$

where $r_{sc}$ = surface resistance of the crop, freely supplied with water, and dense enough for evaporation from the soil to make a negligible contribution

$r_{ss}$ = surface resistance of bare soil (assumed to be 100 $sm^{-1}$ for wet soil)

$A = f^{LAI}$

Grant found that $f$ for barley was about 0.7, and this value is assumed to apply to all the crops treated by MORECS. Eq (4.40) was derived for daytime conditions and assumes that the parallel contributions of soil and crop resistance to their combined resistance are roughly proportional to the amount of incident radiation which each of them absorbs. At night the leaf stomata are closed and the crop resistance $r_{sc}$ is assumed to be the sum of the individual leaf (cuticular) resistances in parallel. These in turn are taken to be directly in parallel with the soil resistance so that

$$1/r_s = 2\xi/r_{sc}(night) + 1/r_{ss} \qquad (4.41)$$

A typical leaf resistance when stomata are closed is several thousand $sm^{-1}$: the form of eq (4.41) used by MORECS is

$$1/r_s = \xi/2500 + 1/r_{ss} \qquad (4.42)$$

It is not possible to justify this last equation convincingly since it ignores the effects of turbulent resistances in the crop canopy. However, evaporation is usually small at night so errors introduced by eq (4.42) will also be small.

Values for $r_{sc}$ which are used by MORECS during the daytime are given in Table 4.2.4. Corresponding values of maximum leaf area index are given in Table 4.2.5.

Leaf areas of the cereals are assumed to increase linearly according to the relation

$$\xi = (\xi_{max} - 0.1)(d - d_e)/(d_f - d_e) + 0.1 \qquad d_e < d < d_f \qquad (4.43)$$

Leaf areas remain unchanged between full development and harvesting, but the effects of senescence are included by writing

$$r_{sc} = r_{sc}(min) + 50\left(\frac{d-d_f}{d_h-d_f}\right) + 500\left(\frac{d-d_f}{d_h-d_f}\right)^3 \qquad (4.44)$$

so that $r_{sc}$ is large ($\simeq$ 600 $sm^{-1}$) at harvest.

Leaf area development for the rootcrops is also represented by eq (4.43), with a constant value after $d = d_f$, but $r_{sc}$ is set to a constant value throughout the season.

Equation (4.43) is also used for deciduous trees during foliation. $r_s$ follows from application of eq (4.40).

Table 4.2.4 Daytime values of surface resistance for dense green crops freely supplied with water

| Type of crop | ($sm^{-1}$) |
|---|---|
| Grass, riparian land | 80 (Jan), 80, 60, 50, 40, 60 (June)<br>60, 70, 70, 70, 80, 80 (Dec) |
| Cereals | 40 |
| Potatoes, sugar beet | 40 |
| Deciduous trees | 80 |
| Conifers | 70[a] |
| Upland[b] | 120 (Jan–Mar, Oct–Dec): 100 (Apr–Sept) |
| Orchards | See text |
| (Bare soil | 100) |
| (Water | 0) |

(a) at zero vapour pressure deficit and 20 deg C: assumed independent of $r_{ss}$, ie $r_s = r_{sc}$

(b) assumed independent of leaf area of ground cover, ie $r_s = r_{sc}$

Table 4.2.5 Maximum leaf area indexes

| Crop | Green leaf area index |
|---|---|
| Grass, riparian land | 2.0 (Jan), 2.0, 3.0, 4.0, 5.0, 5.0 (June)<br>5.0, 5.0, 4.0, 3.0, 2.5, 2.0 (Dec) |
| Cereals | 5.0 |
| Potatoes | 4.0 |
| Sugar beet | 4.0 |
| Deciduous trees | 6.0 |
| Conifers | 6.0[a] |
| Orchards | See text |

(a) constant throughout year

A temperature dependence for $r_{sc}$ in the case of conifers is represented by

$$\left.\begin{array}{ll} r_{sc} = 25\, r_{sc}(min)/(T_{scR}+5) & -5<T_{scR}<20 \\ = r_{sc}(min) & T_{scR}>20 \\ = 10^4 & T_{scR}<-5 \end{array}\right\} \quad (4.45)$$

The well-documented response to vapour pressure deficit (eg Grace et al 1975) is accounted for by writing

$$\left.\begin{array}{ll} r_{sc} = r_{sc}(\delta e=0)/(1-0.05\,\delta e) & \delta e < 20\,mb \\ = 10^4 & \delta e > 20\,mb \end{array}\right\} \quad (4.46)$$

$r_s$ is then calculated using eq (4.40).

Orchards are assumed to be largely grass-covered, so that the values of $r_s$ calculated for grassland are used when the trees are not in leaf. A grass cover with a leaf area index of 2.5 is maintained while the tree leaves develop, and also during the period of tree leaf maturity when the leaf area index of the trees is set to 2.5. Thus the calculation of $r_s$ outside the leafless season has to consider resistances of soil, grass and tree. This is done first by calculating the combined resistance of tree and grass ( $r_s$ (tree/grass)) using the relation

$$1/r_s(tree/grass) = (0.7)^{f_{Lt}}/r_{sc} + (1-(0.7)^{f_{Lt}})/r_{st} \quad (4.47)$$

where

$$f_{Lt} = \left\{\begin{array}{ll} \text{tree leaf area index} & \\ = 2.5(d-d_e)/(d_f-d_e) & d_e<d<d_f \\ = 2.5 & d_f<d<d_L-40 \\ = 2.5\,(d_L-d)/40 & d_L-40<d<d_L \end{array}\right. \quad (4.48)$$

$r_{st}$ = surface resistance of a dense structure of trees (assumed to be 80 $sm^{-1}$)

$r_{sc}$ = surface resistance of a dense grass cover (assumed to be 50 $sm^{-1}$ during the period when the trees are in leaf)

This resistance is combined with soil surface resistance using the relation

$$1/r_s = (0.7)^{f_{Lg}}/r_{ss} + (1-(0.7)^{f_{Lg}})/r_s(tree/grass) \quad (4.49)$$

where $r_{ss} = 100\ sm^{-1}$

$\sum L_{tg}$ = sum of grass and tree leaf area indices

: eq (4.47) and (4.49) reduce to the usual relation for a grass-covered surface (eq (4.40)) when $\sum L_t = 0$.

Night-time values of $r_s$ for permanent crops (conifers, grass, riparian land, upland) are calculated using eq (4.42). Orchard values of $r_s$ at night use the same equation, but with leaf area set equal to the sum of grass and tree leaf areas.

## 4.3 Calculation of actual evaporation using a soil-moisture extraction model

### 4.3.1 Introduction

Numerous experimental studies have shown that evaporation (AE) falls increasingly below the potential rate (PE) as the amount of water available in the soil decreases. The point at which AE begins to depart significantly from PE depends to some extent on the magnitude of the evaporative demand, and the hydraulic properties of the moist soil. The oft-quoted experiment of Denmead and Shaw (1962) showed that AE remained close to PE until most of the available water was exhausted, when the evaporative demand was very low, but that at very high values of demand the AE fell to small values even when considerable amounts of soil moisture remained. These results are consistent with water flowing from moister areas to the root zones of plants at a sufficient rate to maintain plant turgour and hence open stomata only when hydraulic conductivity is large enough to prevent excessive drying out around the roots.

Different soils have not only different volumes of water available to plants, but also different hydraulic conductivities. Sands (low available water capacity) for example are able to sustain relatively high rates of evaporation until much of the available water is exhausted, whereas clays (medium to high available water) with their lower conductivities are associated with AE falling well below PE long before all available water has gone. MORECS performs its calculations for soils of low, medium and high available water content, and for completeness, should perhaps give outputs in each case for low, average and high hydraulic conductivity. This would lead to 9 different sets of outputs, which is an unrealistically large number for this type of operational model. Results are calculated for only "average" hydraulic conductivities there-

fore. The effects noted by Denmead and Shaw are ignored, for two reasons. First, when the evaporative demand is small, for example on humid, cloudy days in summer, or in winter, the soil is usually well supplied with water so that AE $\simeq$ PE regardless of the magnitude of hydraulic conductivity. Second, during the main seasons of evaporation the evaporative demand usually only rises much above the daily average when the soil is very dry; in this last case the evaporative demand may become very large, but AE/PE will then be small due to low available water and the variations of this ratio with hydraulic conductivity will then be of little consequence. If MORECS had been developed for use in climates where very large fluctuations of evaporative demand occur during a season even when considerable amounts of available water remain, then it would have been appropriate to attempt to model the effects noted by Denmead and Shaw for at least average hydraulic conductivities.

### 4.3.2 Relationship between surface resistance and soil moisture deficit

The basis of MORECS' soil moisture extraction model is the assumption that, for a dense crop intercepting the incident radiation completely, the surface resistance remains constant while the first 40% of the available water is extracted but then increases progressively, to very large values when all available water is exhausted. This is broadly consistent with experimental results for crops subjected to a moderate evaporative demand (eg Russell 1980). A similar assumption is made for evaporation of water from bare soil, again in moderate agreement with experiment (Saxton et al 1974), although the quantities of water which may be extracted are smaller here.

Typical crops do not intercept all incident radiation, especially during early growth, and so the contribution to evaporation from the underlying soil must also be considered. This is done by relating $r_{ss}$ to the soil moisture deficit and then combining it with a correspondingly corrected $r_{sc}$, using the relations discussed in § 4.2.2.3.

MORECS uses the simplifying assumption that the available water is held in two reservoirs $X$ and $Y$ which at any time may contain reserves of $x$ and $y$ mm. All water in $X$ is freely available, while that in $Y$ becomes increasingly difficult to extract as $y$ decreases. Thus the

total (maximum) available water ( $x_{max} + y_{max}$ ) is distributed 40% in $X$ and 60% in $Y$. Water is drawn from the soil until $X$ is completely exhausted, when extraction from $Y$ begins. Rainfall is assumed to recharge $X$ first of all, and only replenish $Y$ when $X$ is filled. ( $X$ and $Y$ are sometimes thought of as two discrete soil layers, with $X$ adjacent to the surface and overlying $Y$, but there is no reason why these should be so, and these concepts are deliberately avoided here).

Two distinct cases have to be considered. In the first it is assumed that $X$ contains $x$ mm of water (the quantity in $Y$ is irrelevant here). The values for $r_{sc}$ discussed earlier for potential evaporation will therefore apply because $x$ is greater than zero. However the value of 100 $sm^{-1}$ is only assigned to $r_{ss}$ provided $x_{max}$ is greater than $x(\text{bare soil})_{max}$ : otherwise a rough and arbitrary correction is made by writing

$$r_{ss} = 100\, x_{max} / (x + 0.01\, x_{max}) \qquad sm^{-1} \qquad (4.50)$$

$r_s$ then follows from application of the appropriate equation (usually (4.40). In the second case the water in the top **layer** is exhausted so that $r_{ss} = 10^4\ sm^{-1}$, and $r_{sc}$ is increased according to the size of $y$. The relation used here is derived from data presented by Russell (1980) and is

$$r_{sc}(y) = r_{sc}\left(3.5(1 - y/y_{max}) + \exp(0.2\,(y_{max}/y - 1))\right) \qquad (4.51)$$

When the surface is bare soil (without a crop) the surface resistance is calculated from

$$\left.\begin{aligned} r_s = r_{ss} &= 100\ sm^{-1} \quad (x(\text{bare soil})_{max} > x > 0) \\ &= 100\left(3.5\left(1 - y/y(\text{bare soil})_{max}\right)\right. \\ &\quad \left. + \exp(0.2\,(y(\text{bare soil})_{max}/y - 1))\right) \\ &\quad (x = 0) \end{aligned}\right\} \qquad (4.52)$$

4.3.3 Available soil moisture for different crops

Values of available water capacity selected for MORECS are summarized in Table 4.3.1. Those listed are for soils of medium

Table 4.3.1 MORECS values of available water capacity

| Surface cover | Available water (mm) |
|---|---|
| Grass | 125 |
| Cereals | 140(a) |
| Potatoes | 90(a) |
| Sugar beet | 140(a) |
| Deciduous trees | 175(b) |
| Conifers | 175 |
| Upland | 50 |
| Orchards | 150 |
| Bare soil | 20 |

(a) at maximum rooting depth

(b) at full foliation

capacity: values 25% larger and smaller are used to arbitrarily define soils of high and low capacity. In the case of spring barley and root crops the available water increases from approximately twice that for bare soil at the time of emergence of the crops, linearly to the maximum values given in the Table which are assumed to be achieved when maximum cover is reached ( $d = d_f$ ). After harvest or leaf fall the surface is assumed to return to bare soil. Winter cereals are treated similarly, except that after harvest a bare soil is assumed until the end of December, and thereafter a sparse crop ( $f = 0.5$, $h = 0.08$ m, available water = 3.75 x available water for bare soil) up to the assumed date of start of spring growth. No account is taken of deep rooting by trees which may allow some extraction from potentially much larger reserves in drought conditions.

## 4.4 Calculation of water balance and excess rainfall

### 4.4.1 Treatment of intercepted water, including condensation

When the MORECS estimate of night-time evaporation is negative, $r_s$ is set equal to zero and the calculation performed again in order to provide an estimate of condensation. The treatment of interception is simplified by assuming that the effective daily rainfall is the sum of this condensation and rainfall.

A proportion ( $p$ ) of the effective rainfall is intercepted by the crop overlying the soil, with a dense crop intercepting at a higher rate than a sparse one. The relation used is

$$p = 1 - (0.5)^{\frac{1}{2}\ell} \qquad (p \leq p_{max}) \quad (4.53)$$

Substantial falls of rain will completely wet the canopy and so $p$ is constrained not to exceed that value $p_{max}$ which produces full wetting. This interception capacity is $\gamma\frac{1}{2}\ell$ where $\gamma$ is the capacity per unit leaf area index, assumed to be 0.2 mm. Thus,

$$I = Rp \leq 0.2\,\tfrac{1}{2}\ell \qquad (4.54)$$

where $I$ is the interception and $R$ the rainfall. In practice there may be more than one rainfall event each day, or some evaporation of intercepted water may occur while rain is still falling. In MORECS it is assumed that evaporation of intercepted water is slow in winter months when the maximum daily interception $I_D$ is given by eq (4.53) and (4.54). In summer it is assumed that because of the effect just mentioned, the daily loss will be typically twice the value calculated from (4.53), within the limits $I_D \leq 2I \not> R$ . Factors used to multiply $I$ for each month are given in Table 4.4.1.

Table 4.4.1 Factor enhancing simple interception to allow for multiple daily rainfall events, or for evaporation of intercepted water while rain is falling

| Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor | 1.0 | 1.0 | 1.2 | 1.4 | 1.6 | 2.0 | 2.0 | 2.0 | 1.8 | 1.4 | 1.2 | 1.0 |

Each daytime or night-time calculation is performed with $r_{sc} = 0$ while intercepted water remains. Once the foliage is dry the rate of water loss from the surface is calculated for the remainder of the period using the $r_{sc}$ value for dry foliage. Thus, total water loss from the surface is the sum: intercepted water + (rate of water loss (dry foliage)) x number of hours while foliage is dry. On those occasions when the evaporative demand is insufficient to evaporate all the intercepted water the amount remaining at the end of the day is not carried over but is assumed to fall to the soil.

### 4.4.2 Soil moisture deficit and excess rainfall

The information given in previous sections explains how the daily evaporation is calculated. The difference between this evaporation and rainfall, when added to the previous day's soil moisture deficit, yields the current soil moisture deficit. Some clarification of this procedure is required for seasonal crops after harvest, before emergence of the new crop. In this period there will be reserves $x$ mm in reservoir $X_{crop}$ and $y$ mm in $Y_{crop}$. Until the newly-sown crop emerges it is assumed that there is no root system which can extract moisture from $Y_{crop}$: over this period then the only change to $y$ will be increases due to any rainfall remaining after $X_{crop}$ is filled. Also the absence of a root system usually means that $X_{crop}$ will not be fully available for evaporation. Thus the maximum amount of available water after harvest, all assumed residing in a part of $X_{crop}$, is the fraction

$$(x(\text{bare soil})_{max} + y(\text{bare soil})_{max}) \cdot x/x_{max}$$

: the remainder of the water in $X_{crop}$ is not available, and can only be changed by residual rainfall which remains after the other part of $X_{crop}$ (that available for bare soil evaporation) is replenished. Thus the fraction of the $X_{crop}$ water, calculated as above at harvest, is assumed transferred to two reservoirs $X(\text{bare soil})$ and $Y(\text{bare soil})$ in the proportions 60% : 40%.

Rainfall is assumed to fill first $X$, then $Y$, at a very rapid rate (in the case of bare soil after the harvest, rain will fill $X$, $Y(\text{bare soil})$, then the remaining part of $X_{crop}$ and finally

$Y_{crop}$ . The excess rain after these reservoirs are replenished (at which point the soil will be at field capacity) is assumed to be "hydrologically effective rainfall".

No attempt is made to model or estimate run-off.

4.4.3 Calculation of real land use values of PE, AE, SMD and HER

Real land use values of PE, AE, SMD and HER are calculated for each square using estimates of percentage of various surfaces in each square (Annexe B). The estimates were obtained from a variety of sources. The 14 real land use types are correlated with the 12 surfaces types used in MORECS according to Table 4.4.2.

Table 4.4.2 Relation between real land use and MORECS surface types

| Real land use | Representation in MORECS outputs |
|---|---|
| 1. Impervious urban | Impervious urban (page 57) |
| 2. Open water | Open water |
| 3. Riparian | Riparian |
| 4. Bare Rock | Bare rock (page 57) |
| 5. Conifers | Conifers |
| 6. Heather, gorse | Upland |
| 7. Permanent grass | Grass |
| 8. Deciduous trees | Deciduous trees |
| 9. Orchards | Orchards |
| 10. Rough grazing | Upland |
| 11. Cereals | ((Winter wheat + winter barley)/2 + spring barley)/2 |
| 12. Potatoes | (Main crop + earlies)/2 |
| 13. Temporary grass | Grass |
| 14. Fallow | Bare soil |

Real land use estimates of PE, AE, SMD and HER for each square are obtained from the MORECS outputs weighted according to Table 4.4.1 and the percentages given in Annexe B, and then summed.

## 4.5 MORECS outputs

MORECS users have widely different applications for its outputs so a number of output options are provided. This number has to be limited, for operational reasons, but the information provided caters for most of the needs which have been expressed.

At present there are five options available, which provide data in both tabular and graphical (map) form.

(i) Weekly issues of 13 maps showing, for soils of medium available water capacity, grid square values of PE, AE, SMD and HER for grassland and real land use, and square values of the 5 basic meteorological variables (sunshine, temperature, vapour pressure, wind speed and rainfall): a written commentary is included fortnightly and summary maps monthly (total PE, AE and HER for the month, end of month SMD for grass, average daily temperature, vapour pressure and wind, total sunshine and rainfall)

(ii) As (i), but without the maps referring to real land use

(iii) Fortnightly issues of 3 maps showing PE for grass, and SMD for grass and real land use, together with the written commentary

(iv) Weekly issues giving in tabular form PE, AE, SMD and HER for 3 soils and 13 crops/surface types, plus values of the meteorological variables, one square per sheet

(v) A table on 6 sheets, issued weekly, showing for soils with medium available water capacity PE, AE and SMD for six crops, and also the meteorological data, for all 190 MORECS squares.

A selection of one or more of these options satisfies the requirements of most users.

Examples of forms of output are given in Annexe C.

## 4.6 Comparisons between MORECS outputs and neutron probe data

Some 25 station years of neutron probe SMD data were used in the verification of the MORECS model. The field data covered several crop types and a variety of soils during the period 1970 to 1980. Results of the comparisons which are presented here refer to at least one set of

neutron probe data for each of the years for which probe data are available (Table 4.6.1).

Table 4.6.1 Neutron probe data

| | Year | Place | Crop | Soil AWC |
|---|---|---|---|---|
| 1. | 1970 | Sutton Bonington | Spring barley | Low |
| 2. | 1972 | Sutton Bonington | Spring barley | Low |
| 3. | 1975 | Sutton Bonington | Winter wheat | Medium |
| 4. | 1976 | Sutton Bonington | Winter wheat | Medium |
| 5. | 1976 | Broom's Barn | Sugar beet | High |
| 6. | 1977 | Westbury-on-Trym | Grass | High |
| 7. | 1978 | Near Finningley | Potatoes | Medium |
| 8. | 1979 | Broom's Barn | Sugar beet | High |
| 9. | 1980 | Hurley | Grass | High |
| 10. | 1981 | Hurley | Grass | High |

Probe SMD's were compared with estimates obtained using the MORECS routines (Annexe D); the input meteorological data were those from the observing station nearest each probe site. However, rainfall data from, or near, the actual probe sites were used where available (exceptions are listed in the Annexe). The standard MORECS available water capacities, sowing and harvesting dates (Annexe A) were used unless these differed markedly from the actual data, which were then used instead.

Inspection of the diagrams in Annexe D indicates the success with which MORECS performs. Some of the anomalies can be clearly attributed to the employment of rainfall figures which were not obtained at the actual probe site (eg Sutton Bonington 1972, during the first part of June). There are other anomalies, but the evidence from these 10 cases, and from others used but not presented here, supports on the whole the idea that this new version of MORECS gives generally acceptable values of SMD.

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* Available from National Meteorological Library, Bracknell.

## Annexe A Dates assumed for crop development

This annexe gives the year days (eg 365 = 31 December) (Table A2) for each grid square for sowing, harvesting etc of the various crops. Intermediate stages are determined from these year days, using the information given in Table A1.

Table A1 Year days for emergence etc

| Crop | day of sowing ($d_s$) | Start of spring growth, or emergence | day full cover is reached ($d_f$) | day of harvest ($d_h$) |
|---|---|---|---|---|
| Spring barley | * | $d_s + 15$ | $d_h - 60$ | * |
| Winter wheat | * | $d_h - 156$ | $d_h - 60$ | * |
| Winter barley | * | $d_h - 145$ | $d_h - 60$ | * |
| Early potatoes | * | $d_s + 25$ | $d_s + 90$ | * |
| Main crop potatoes | * | $d_s + 25$ | $d_s + 90$ | * |
| Sugar beet | * | $d_s + 64$ | $d_s + 101$ | * |

* obtained from figures A1-A6

Orchards and deciduous trees (figures A7, A8) are treated by assuming that 40 days elapse between bud burst and full cover, and also between onset of autumn senescence and complete leaf fall.

Winter cereals are assumed to emerge on 1 January, obviously later than reality, but this makes a negligible difference to calculated PE etc in autumn and early winter, and allows a substantial simplication of the computer routines.

Take as an illustrative example spring barley growing in square 94. Then Table A1 and figure A1 give the following dates

| | Year Day | Date |
|---|---|---|
| Sown | 80 | 21 March |
| Emerged | 95 | 5 April |
| Full cover | 176 | 25 June |
| Harvest | 236 | 24 August |

(-1 in any square in figures A1-A8 indicates that the crop in question is grown in insignificant quantities in that square).

Table A2

DATE TO DAY OF YEAR

| DATE | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | DATE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 32 | 60 | 91 | 121 | 152 | 182 | 213 | 244 | 274 | 305 | 335 | 1 |
| 2 | 2 | 33 | 61 | 92 | 122 | 153 | 183 | 214 | 245 | 275 | 306 | 336 | 2 |
| 3 | 3 | 34 | 62 | 93 | 123 | 154 | 184 | 215 | 246 | 276 | 307 | 337 | 3 |
| 4 | 4 | 35 | 63 | 94 | 124 | 155 | 185 | 216 | 247 | 277 | 308 | 338 | 4 |
| 5 | 5 | 36 | 64 | 95 | 125 | 156 | 186 | 217 | 248 | 278 | 309 | 339 | 5 |
| 6 | 6 | 37 | 65 | 96 | 126 | 157 | 187 | 218 | 249 | 279 | 310 | 340 | 6 |
| 7 | 7 | 38 | 66 | 97 | 127 | 158 | 188 | 219 | 250 | 280 | 311 | 341 | 7 |
| 8 | 8 | 39 | 67 | 98 | 128 | 159 | 189 | 220 | 251 | 281 | 312 | 342 | 8 |
| 9 | 9 | 40 | 68 | 99 | 129 | 160 | 190 | 221 | 252 | 282 | 313 | 343 | 9 |
| 10 | 10 | 41 | 69 | 100 | 130 | 161 | 191 | 222 | 253 | 283 | 314 | 344 | 10 |
| 11 | 11 | 42 | 70 | 101 | 131 | 162 | 192 | 223 | 254 | 284 | 315 | 345 | 11 |
| 12 | 12 | 43 | 71 | 102 | 132 | 163 | 193 | 224 | 255 | 285 | 316 | 346 | 12 |
| 13 | 13 | 44 | 72 | 103 | 133 | 164 | 194 | 225 | 256 | 286 | 317 | 347 | 13 |
| 14 | 14 | 45 | 73 | 104 | 134 | 165 | 195 | 226 | 257 | 287 | 318 | 348 | 14 |
| 15 | 15 | 46 | 74 | 105 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 | 15 |
| 16 | 16 | 47 | 75 | 106 | 136 | 167 | 197 | 228 | 259 | 289 | 320 | 350 | 16 |
| 17 | 17 | 48 | 76 | 107 | 137 | 168 | 198 | 229 | 260 | 290 | 321 | 351 | 17 |
| 18 | 18 | 49 | 77 | 108 | 138 | 169 | 199 | 230 | 261 | 291 | 322 | 352 | 18 |
| 19 | 19 | 50 | 78 | 109 | 139 | 170 | 200 | 231 | 262 | 292 | 323 | 353 | 19 |
| 20 | 20 | 51 | 79 | 110 | 140 | 171 | 201 | 232 | 263 | 293 | 324 | 354 | 20 |
| 21 | 21 | 52 | 80 | 111 | 141 | 172 | 202 | 233 | 264 | 294 | 325 | 355 | 21 |
| 22 | 22 | 53 | 81 | 112 | 142 | 173 | 203 | 234 | 265 | 295 | 326 | 356 | 22 |
| 23 | 23 | 54 | 82 | 113 | 143 | 174 | 204 | 235 | 266 | 296 | 327 | 357 | 23 |
| 24 | 24 | 55 | 83 | 114 | 144 | 175 | 205 | 236 | 267 | 297 | 328 | 358 | 24 |
| 25 | 25 | 56 | 84 | 115 | 145 | 176 | 206 | 237 | 268 | 298 | 329 | 359 | 25 |
| 26 | 26 | 57 | 85 | 116 | 146 | 177 | 207 | 238 | 269 | 299 | 330 | 360 | 26 |
| 27 | 27 | 58 | 86 | 117 | 147 | 178 | 208 | 239 | 270 | 300 | 331 | 361 | 27 |
| 28 | 28 | 59 | 87 | 118 | 148 | 179 | 209 | 240 | 271 | 301 | 332 | 362 | 28 |
| 29 | 29 | | 88 | 119 | 149 | 180 | 210 | 241 | 272 | 302 | 333 | 363 | 29 |
| 30 | 30 | | 89 | 120 | 150 | 191 | 211 | 242 | 273 | 303 | 334 | 364 | 30 |
| 31 | 31 | | 90 | | 151 | | 212 | 243 | | 304 | | 365 | |

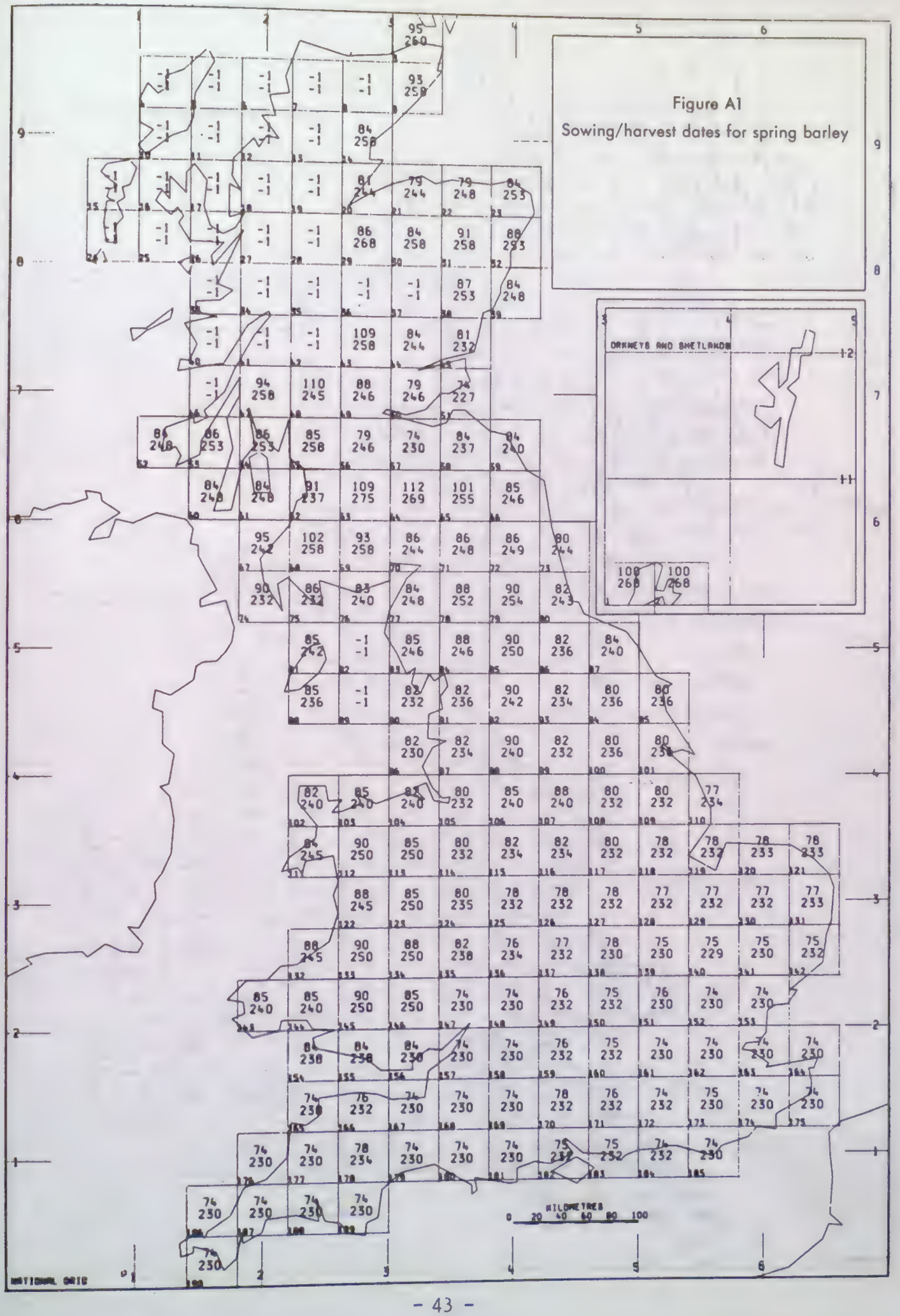



Figure A1

Sowing/harvest dates for spring barley

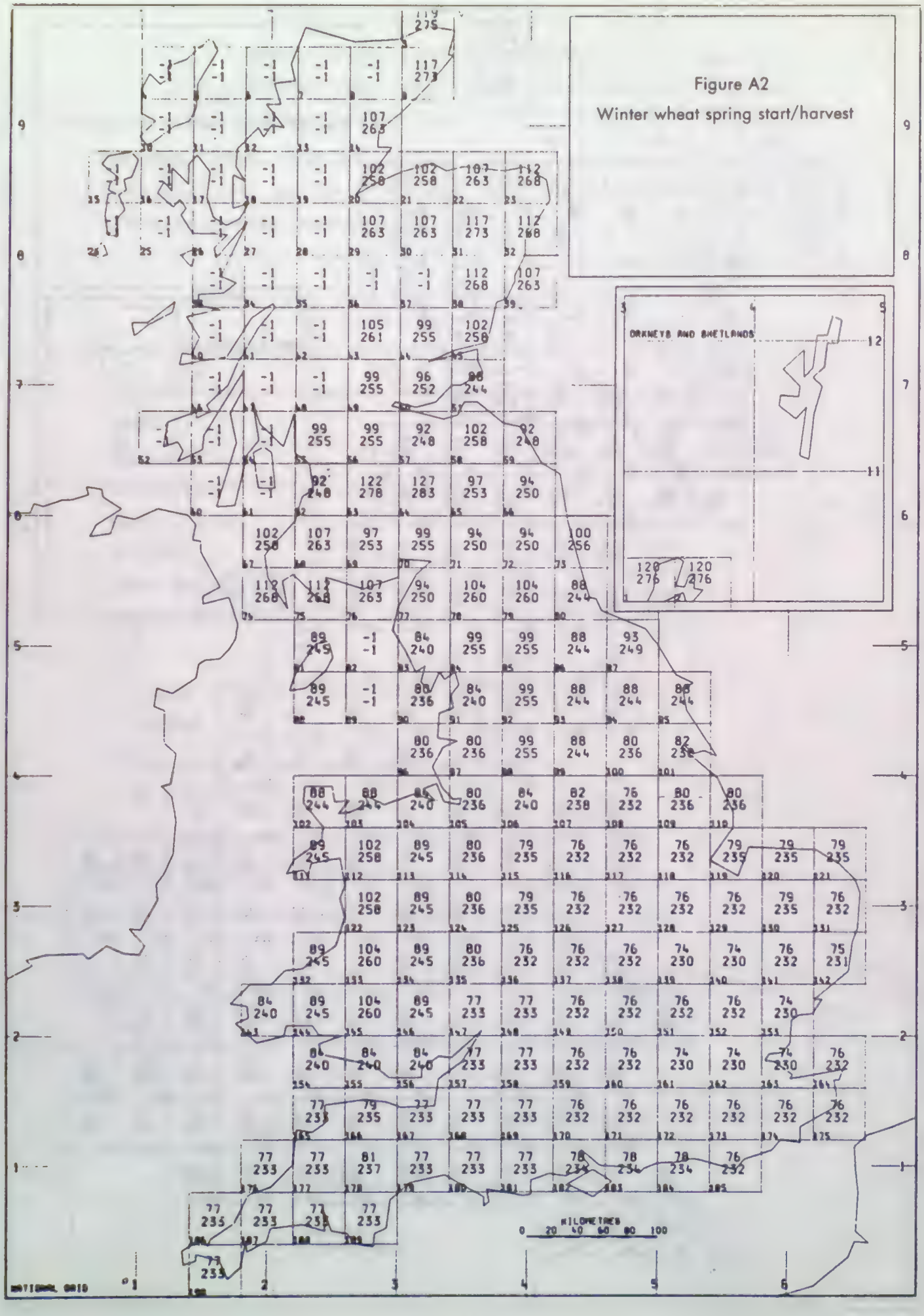


Figure A2
Winter wheat spring start/harvest
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100

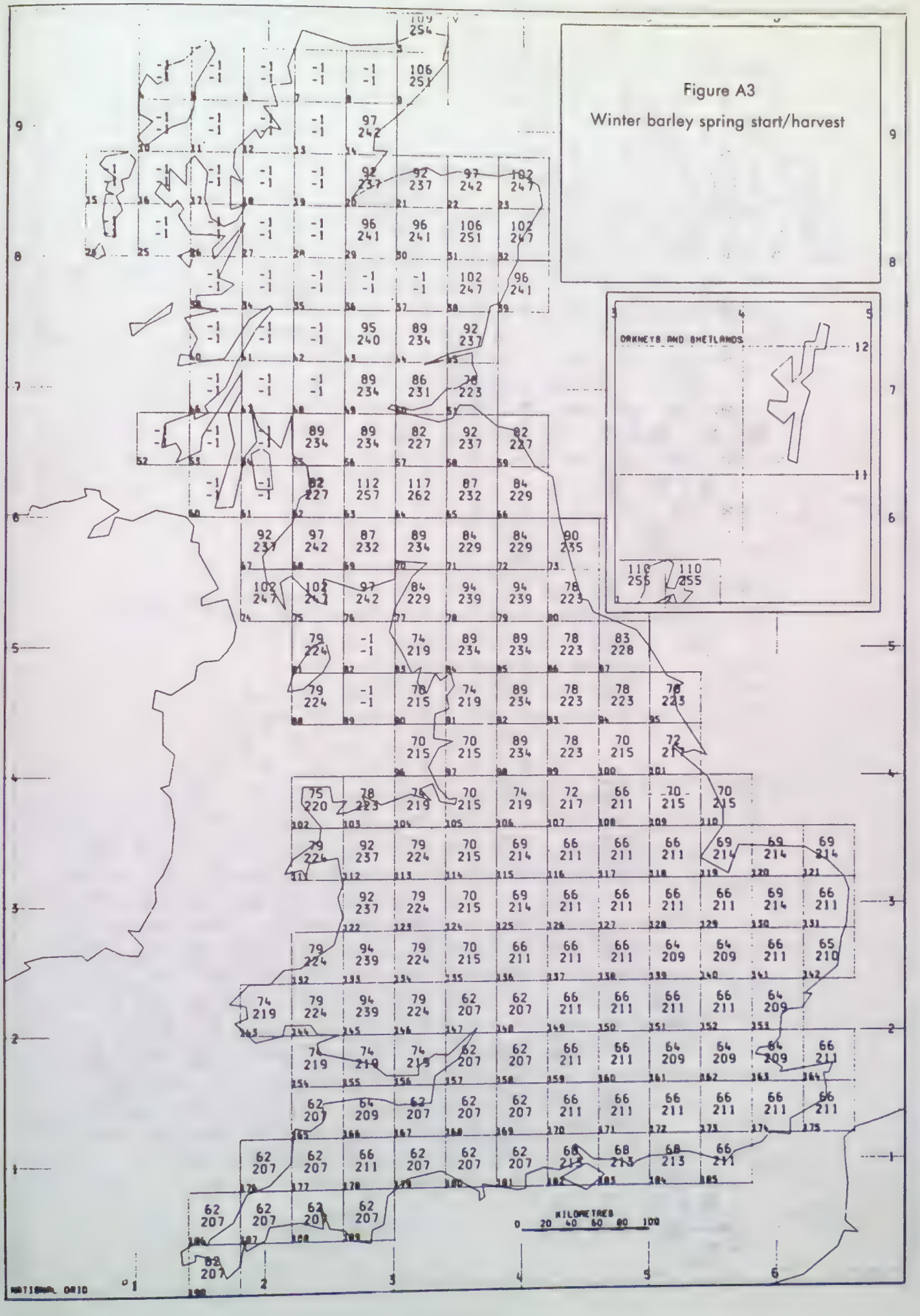


Figure A3
Winter barley spring start/harvest
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100

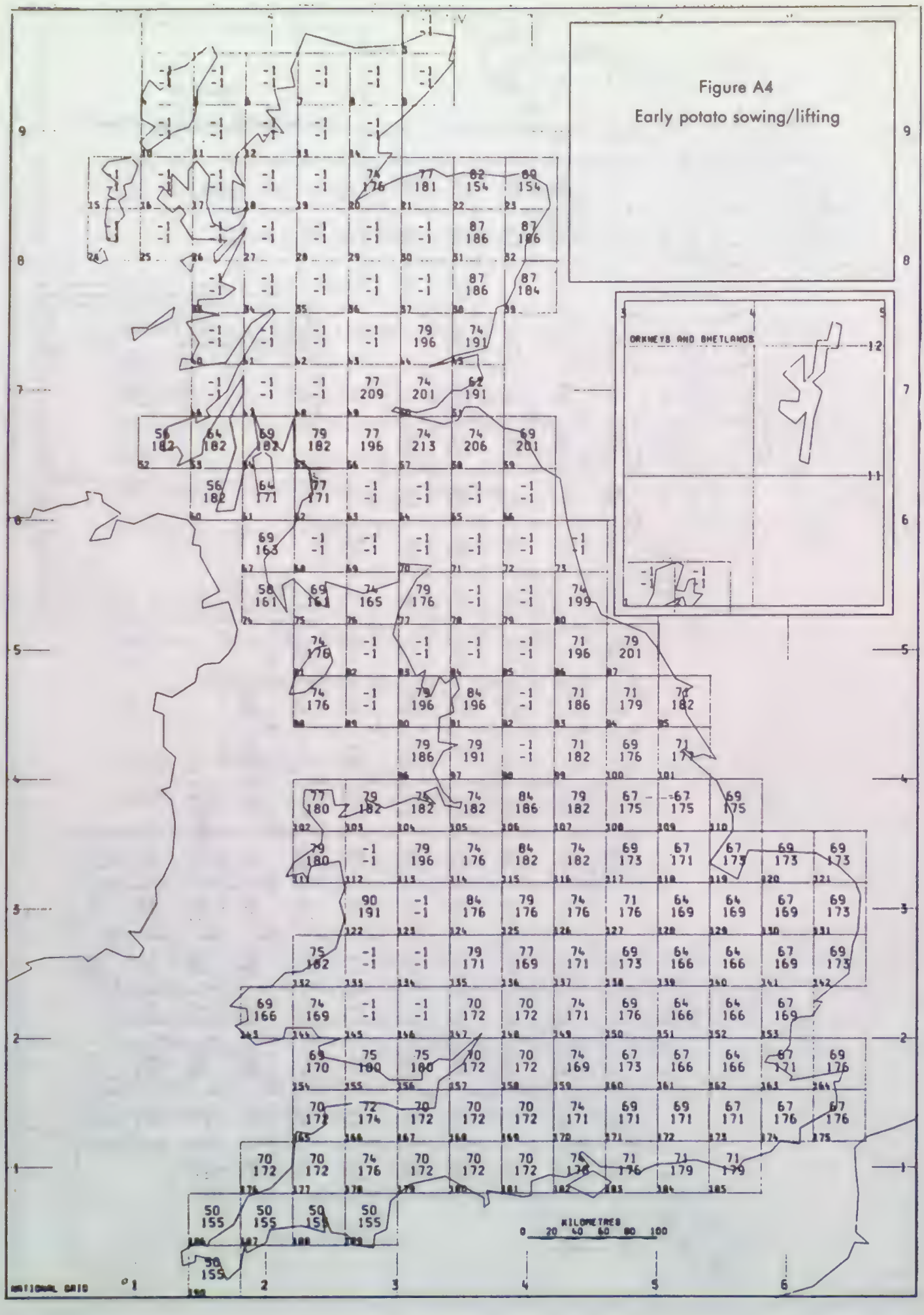



Figure A4

Early potato sowing/lifting

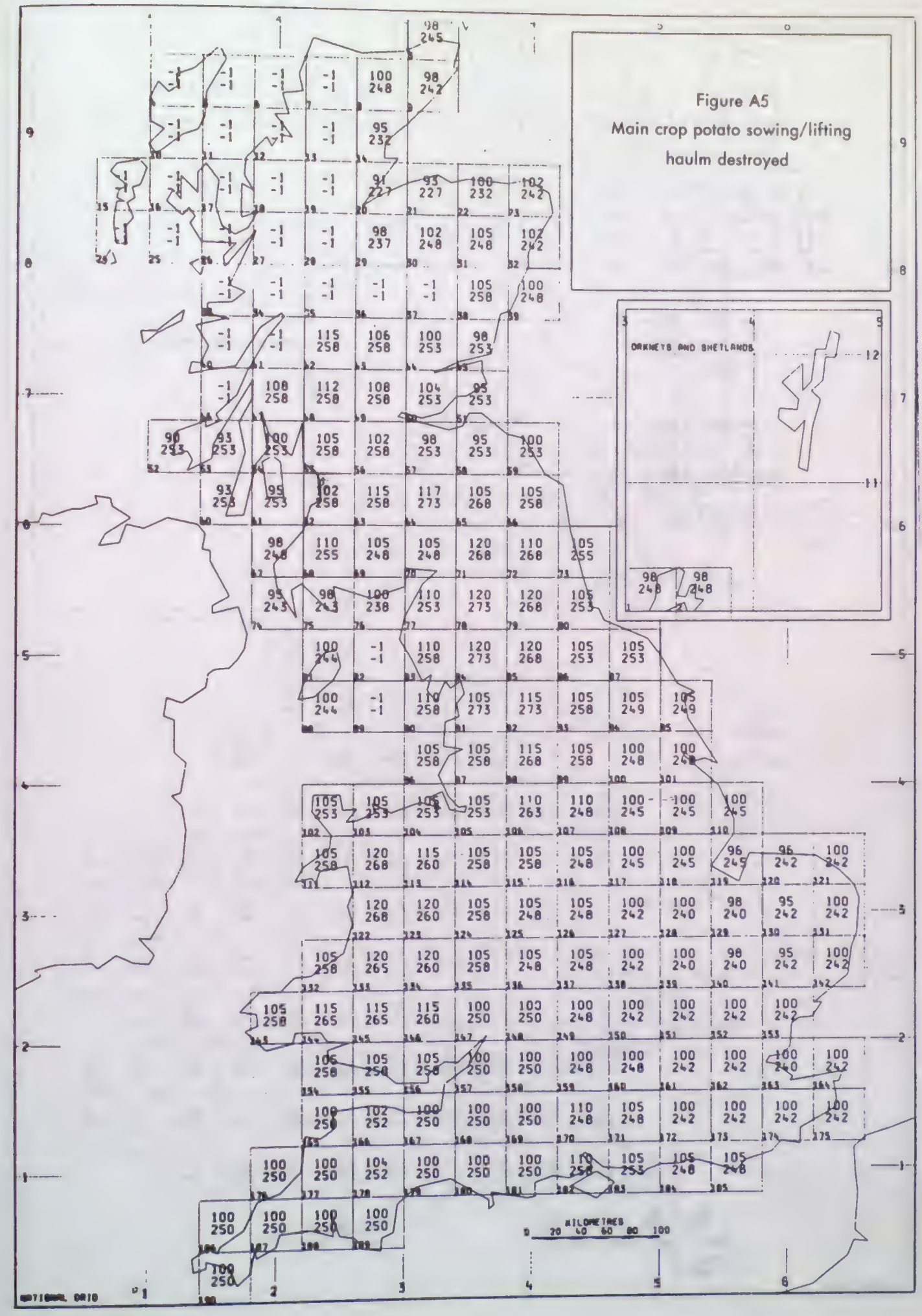


Figure A5
Main crop potato sowing/lifting
haulm destroyed
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100

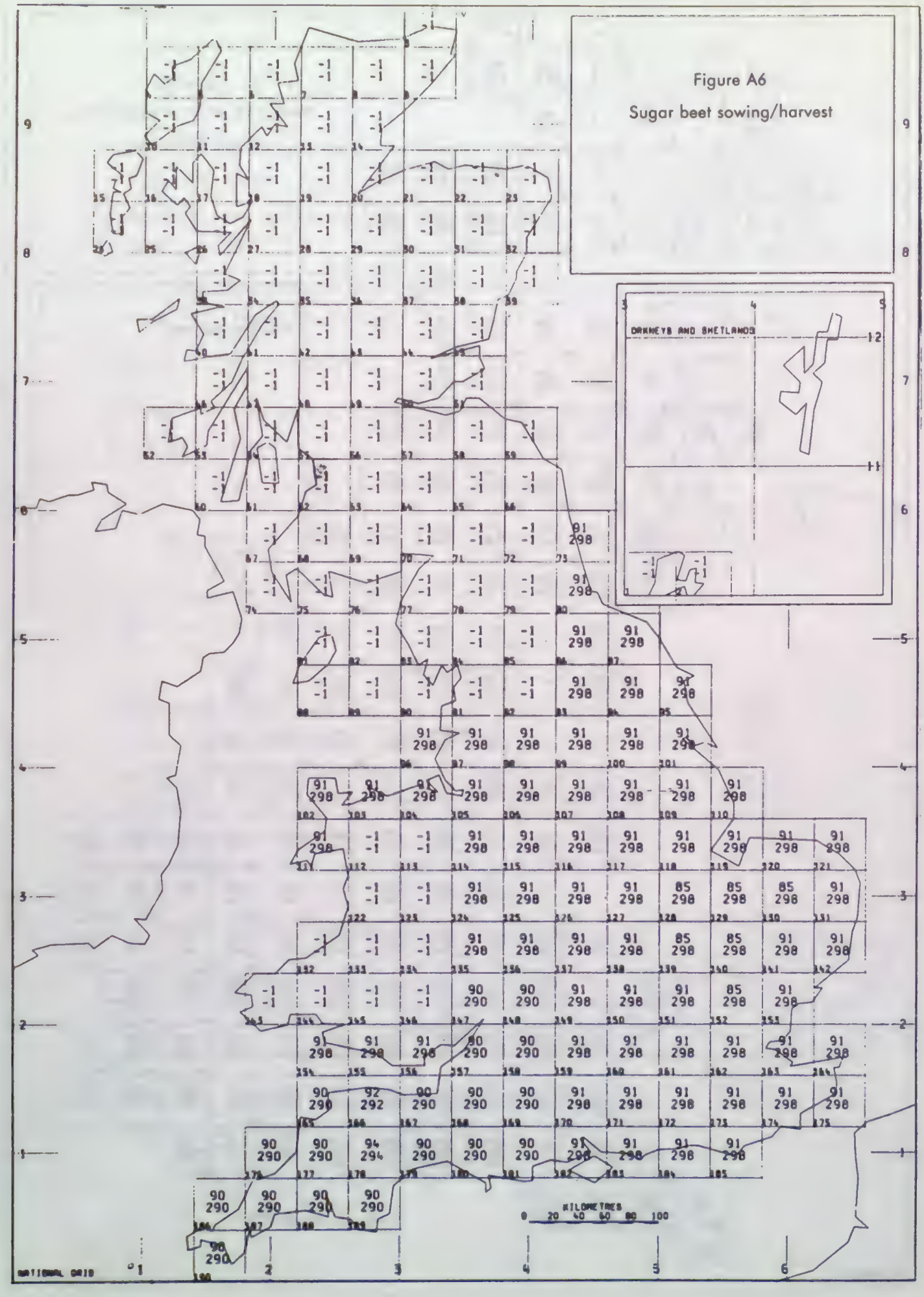


Figure A6
Sugar beet sowing/harvest
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100

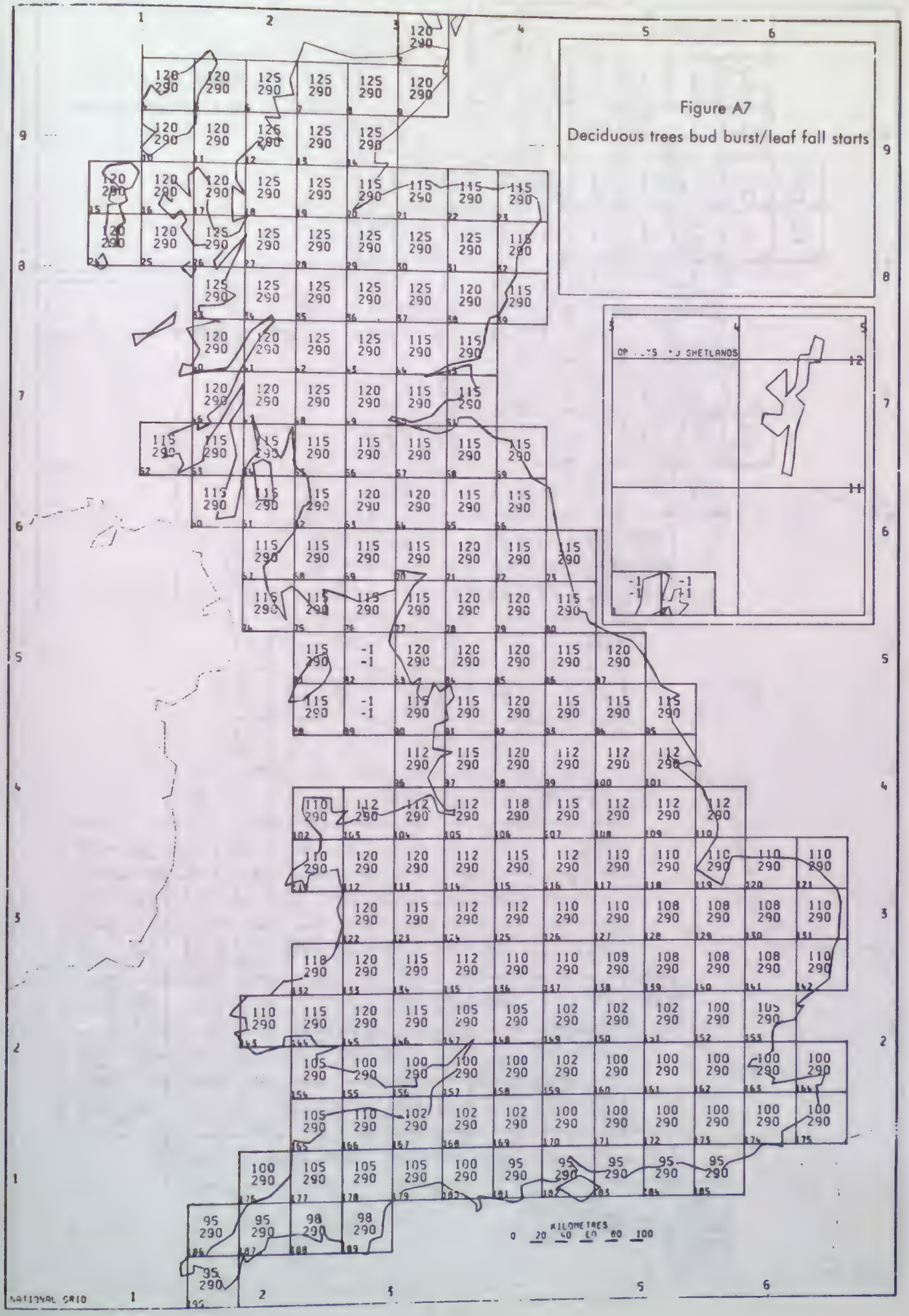


Figure A7
Deciduous trees bud burst/leaf fall starts
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

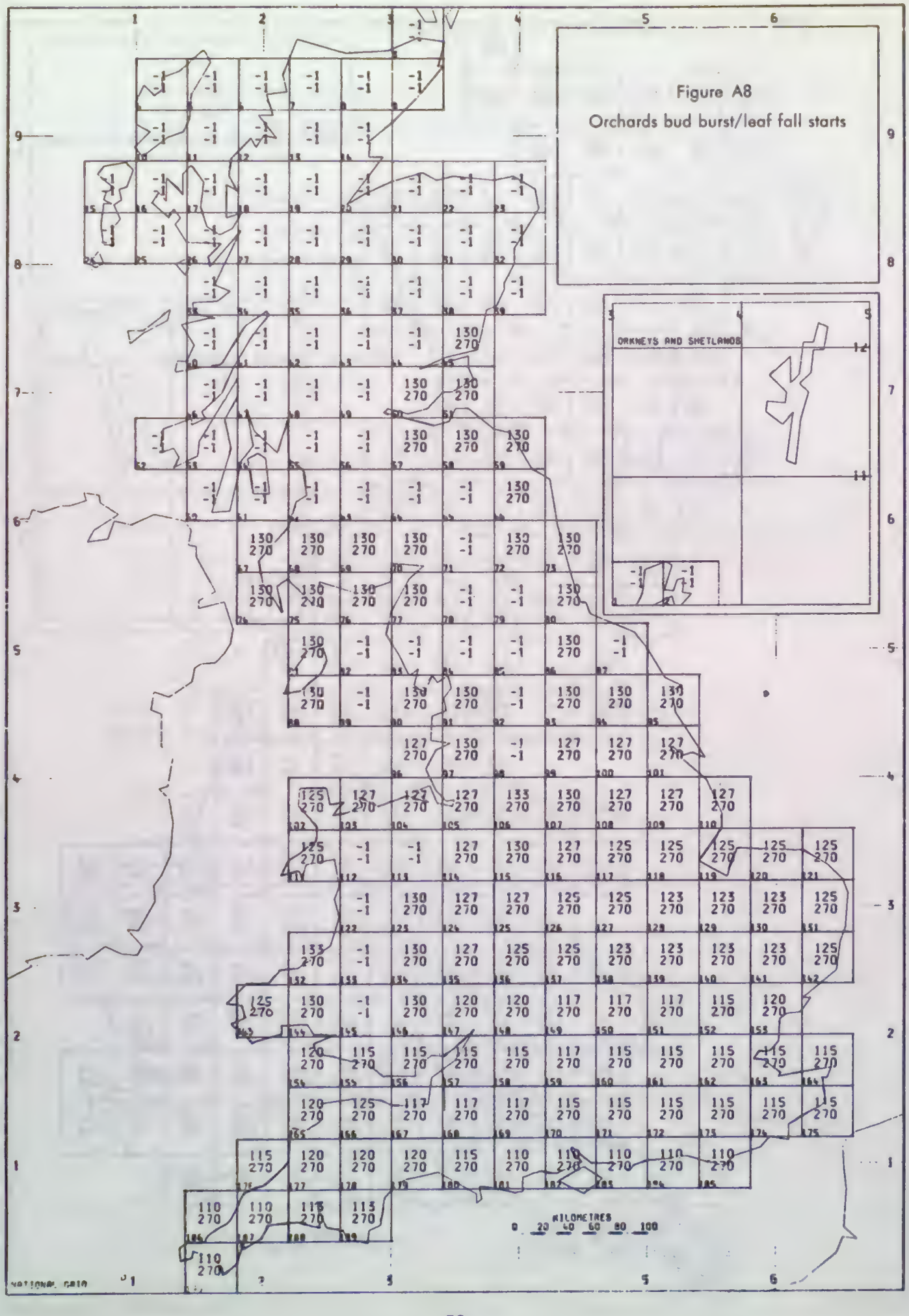


Figure A8
Orchards bud burst/leaf fall starts
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

ANNEXE B Estimates of percentage of land use types in each MORECS square

LAND USE KEY

| No | LAND USE |
|---|---|
| 1 | URBAN |
| 2 | OPEN WATER |
| 3 | RIPERIAN |
| 4 | ROCK |
| 5 | CONIFEROUS WOODLAND |
| 6 | HEATHER, GORSE |
| 7 | PERMANENT GRASS |
| 8 | DECIDUOUS WOODLAND |
| 9 | ORCHARDS |
| 10 | ROUGH GRAZING |
| 11 | CEREALS |
| 12 | MAIN CROP POTATOES |
| 13 | TEMPORARY GRASS |
| 14 | FALLOW, BARE GROUND |

| SQUARE NO. | PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LAND USE (SEE KEY) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 1 | 0 | 3 | 3 | 0 | 5 | 12 | 12 | 0 | 0 | 20 | 13 | 2 | 30 | 0 |
| 2 | 0 | 0 | 2 | 0 | 5 | 9 | 15 | 0 | 0 | 15 | 16 | 3 | 35 | 0 |
| 3 | 0 | 2 | 3 | 1 | 5 | 4 | 17 | 0 | 0 | 30 | 15 | 3 | 20 | 0 |
| 4 | 0 | 3 | 2 | 1 | 2 | 12 | 16 | 0 | 0 | 60 | 2 | 1 | 1 | 0 |
| 5 | 0 | 3 | 2 | 0 | 2 | 15 | 13 | 0 | 0 | 61 | 2 | 1 | 1 | 0 |
| 6 | 0 | 3 | 2 | 0 | 2 | 13 | 10 | 0 | 0 | 69 | 0 | 0 | 1 | 0 |
| 7 | 0 | 3 | 2 | 3 | 6 | 10 | 15 | 0 | 0 | 60 | 0 | 0 | 1 | 0 |
| 8 | 0 | 3 | 2 | 2 | 8 | 12 | 11 | 0 | 0 | 61 | 0 | 1 | 0 | 0 |
| 9 | 0 | 2 | 3 | 0 | 5 | 7 | 17 | 0 | 0 | 57 | 4 | 1 | 4 | 0 |
| 10 | 0 | 3 | 2 | 2 | 2 | 17 | 11 | 0 | 0 | 61 | 1 | 0 | 1 | 0 |
| 11 | 0 | 0 | 3 | 1 | 2 | 10 | 11 | 0 | 0 | 69 | 2 | 1 | 1 | 0 |
| 12 | 0 | 5 | 3 | 4 | 8 | 5 | 14 | 0 | 0 | 58 | 1 | 1 | 1 | 0 |
| 13 | 0 | 3 | 3 | 5 | 10 | 12 | 13 | 0 | 0 | 51 | 1 | 1 | 1 | 0 |
| 14 | 0 | 0 | 3 | 0 | 7 | 6 | 12 | 0 | 0 | 67 | 0 | 0 | 5 | 0 |
| 15 | 0 | 3 | 3 | 0 | 2 | 30 | 12 | 0 | 0 | 48 | 0 | 0 | 2 | 0 |
| 16 | 0 | 0 | 3 | 0 | 8 | 20 | 11 | 0 | 0 | 56 | 0 | 0 | 2 | 0 |
| 17 | 0 | 0 | 3 | 3 | 8 | 8 | 13 | 0 | 0 | 65 | 0 | 0 | 0 | 0 |
| 18 | 0 | 3 | 3 | 5 | 8 | 13 | 10 | 0 | 0 | 55 | 2 | 1 | 0 | 0 |
| 19 | 0 | 3 | 2 | 4 | 12 | 14 | 10 | 0 | 0 | 43 | 8 | 4 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 21 | 2 | 10 | 0 | 0 | 12 | 27 | 9 | 19 | 0 |
| 21 | 0 | 0 | 1 | 0 | 12 | 5 | 16 | 1 | 0 | 24 | 24 | 6 | 11 | 0 |
| 22 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 2 | 0 | 0 | 42 | 13 | 33 | 0 |
| 23 | 0 | 1 | 0 | 0 | 10 | 9 | 3 | 1 | 0 | 3 | 40 | 9 | 24 | 0 |
| 24 | 0 | 3 | 0 | 0 | 10 | 18 | 16 | 0 | 0 | 53 | 0 | 0 | 0 | 0 |
| 25 | 0 | 0 | 1 | 2 | 10 | 22 | 15 | 0 | 0 | 50 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 0 | 4 | 8 | 19 | 13 | 0 | 0 | 56 | 0 | 0 | 0 | 0 |
| 27 | 0 | 3 | 0 | 4 | 10 | 20 | 12 | 0 | 0 | 48 | 2 | 1 | 0 | 0 |
| 28 | 0 | 8 | 0 | 2 | 15 | 11 | 13 | 0 | 0 | 51 | 0 | 0 | 0 | 0 |
| 29 | 0 | 3 | 2 | 4 | 16 | 5 | 14 | 0 | 0 | 54 | 2 | 0 | 0 | 0 |
| 30 | 0 | 0 | 3 | 2 | 15 | 15 | 21 | 1 | 0 | 29 | 12 | 2 | 0 | 0 |
| 31 | 0 | 0 | 0 | 0 | 10 | 7 | 8 | 1 | 0 | 7 | 37 | 9 | 21 | 0 |
| 32 | 4 | 0 | 0 | 0 | 8 | 0 | 16 | 1 | 0 | 9 | 34 | 8 | 20 | 0 |
| 33 | 0 | 8 | 1 | 5 | 3 | 20 | 13 | 0 | 0 | 50 | 0 | 0 | 0 | 0 |
| 34 | 0 | 4 | 3 | 2 | 10 | 13 | 11 | 0 | 0 | 57 | 0 | 0 | 0 | 0 |
| 35 | 0 | 5 | 3 | 5 | 12 | 20 | 18 | 0 | 0 | 37 | 0 | 0 | 0 | 0 |
| 36 | 0 | 0 | 4 | 3 | 11 | 5 | 20 | 1 | 0 | 48 | 4 | 2 | 2 | 0 |

| SQUARE NO. | PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LAND USE (SEE KEY) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 37 | 0 | 0 | 2 | 3 | 15 | 3 | 19 | 1 | 0 | 30 | 15 | 5 | 7 | 0 |
| 38 | 0 | 0 | 2 | 0 | 16 | 3 | 15 | 1 | 0 | 32 | 17 | 6 | 8 | 0 |
| 39 | 0 | 0 | 0 | 0 | 7 | 5 | 33 | 1 | 0 | 12 | 24 | 7 | 11 | 0 |
| 40 | 0 | 2 | 2 | 5 | 15 | 15 | 15 | 2 | 0 | 44 | 0 | 0 | 0 | 0 |
| 41 | 0 | 2 | 2 | 5 | 15 | 15 | 19 | 2 | 0 | 40 | 0 | 0 | 0 | 0 |
| 42 | 0 | 2 | 2 | 4 | 10 | 10 | 17 | 2 | 0 | 47 | 3 | 1 | 2 | 0 |
| 43 | 0 | 2 | 2 | 4 | 10 | 3 | 18 | 1 | 0 | 49 | 6 | 2 | 3 | 0 |
| 44 | 1 | 0 | 0 | 0 | 10 | 3 | 13 | 1 | 0 | 19 | 29 | 12 | 12 | 0 |
| 45 | 1 | 0 | 0 | 0 | 8 | 0 | 17 | 1 | 0 | 4 | 39 | 16 | 14 | 0 |
| 46 | 0 | 0 | 2 | 1 | 9 | 16 | 19 | 2 | 0 | 51 | 0 | 0 | 0 | 0 |
| 47 | 0 | 2 | 0 | 2 | 20 | 20 | 21 | 2 | 0 | 33 | 0 | 0 | 0 | 0 |
| 48 | 0 | 4 | 2 | 0 | 18 | 2 | 24 | 1 | 0 | 42 | 3 | 1 | 3 | 0 |
| 49 | 1 | 2 | 3 | 0 | 6 | 3 | 23 | 1 | 0 | 47 | 7 | 2 | 5 | 0 |
| 50 | 3 | 2 | 1 | 0 | 6 | 0 | 16 | 1 | 0 | 20 | 29 | 10 | 12 | 0 |
| 51 | 0 | 0 | 0 | 0 | 3 | 0 | 16 | 1 | 0 | 5 | 48 | 14 | 13 | 0 |
| 52 | 0 | 2 | 2 | 0 | 8 | 5 | 19 | 2 | 0 | 57 | 5 | 0 | 0 | 0 |
| 53 | 0 | 0 | 3 | 4 | 10 | 10 | 15 | 2 | 0 | 56 | 0 | 0 | 0 | 0 |
| 54 | 0 | 0 | 2 | 3 | 12 | 18 | 13 | 2 | 0 | 40 | 0 | 0 | 10 | 0 |
| 55 | 6 | 0 | 3 | 0 | 5 | 0 | 31 | 1 | 0 | 35 | 9 | 2 | 8 | 0 |
| 56 | 0 | 0 | 3 | 0 | 8 | 0 | 28 | 1 | 0 | 16 | 23 | 4 | 17 | 0 |
| 57 | 5 | 1 | 3 | 0 | 5 | 5 | 28 | 1 | 0 | 26 | 14 | 5 | 7 | 0 |
| 58 | 0 | 0 | 3 | 0 | 5 | 0 | 19 | 1 | 0 | 28 | 24 | 6 | 14 | 0 |
| **59** | **1** | **0** | **3** | **0** | **8** | **1** | **22** | **5** | **0** | **11** | **27** | **5** | **17** | **0** |
| **60** | **0** | **0** | **3** | **0** | **10** | **5** | **17** | **2** | **0** | **52** | **5** | **6** | **0** | **0** |
| 61 | 0 | 0 | 3 | 0 | 10 | 15 | 12 | 2 | 0 | 50 | 2 | 1 | 5 | 0 |
| 62 | 0 | 0 | 4 | 0 | 10 | 11 | 27 | 1 | 0 | 32 | 5 | 1 | 9 | 0 |
| 63 | 0 | 0 | 3 | 0 | 8 | 5 | 25 | 1 | 0 | 44 | 4 | 1 | 9 | 0 |
| 64 | 0 | 0 | 3 | 0 | 12 | 4 | 19 | 1 | 0 | 51 | 3 | 3 | 4 | 0 |
| 65 | 0 | 0 | 3 | 0 | 10 | 9 | 20 | 1 | 0 | 37 | 10 | 3 | 7 | 0 |
| 66 | 0 | 0 | 0 | 0 | 7 | 3 | 23 | 4 | 0 | 37 | 12 | 3 | 11 | 0 |
| 67 | 0 | 0 | 3 | 0 | 10 | 6 | 29 | 1 | 0 | 36 | 5 | 1 | 9 | 0 |
| 68 | 0 | 1 | 3 | 0 | 10 | 15 | 20 | 1 | 0 | 40 | 4 | 1 | 5 | 0 |
| 69 | 0 | 0 | 3 | 0 | 10 | 9 | 25 | 1 | 0 | 38 | 5 | 1 | 8 | 0 |
| 70 | 0 | 0 | 2 | 0 | 7 | 7 | 17 | 1 | 0 | 39 | 9 | 2 | 16 | 0 |
| 71 | 0 | 0 | 2 | 0 | 10 | 4 | 31 | 2 | 0 | 37 | 6 | 2 | 6 | 0 |

| SQUARE NO. | PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LAND USE (SEE KEY) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 72 | 2 | 0 | 0 | 0 | 10 | 12 | 36 | 4 | 0 | 19 | 7 | 2 | 8 | 0 |
| 73 | 16 | 0 | 0 | 0 | 0 | 0 | 49 | 4 | 0 | 2 | 6 | 0 | 23 | 0 |
| 74 | 0 | 0 | 0 | 0 | 9 | 4 | 3 | 1 | 0 | 3 | 0 | 13 | 67 | 0 |
| 75 | 0 | 1 | 3 | 0 | 9 | 7 | 28 | 1 | 0 | 19 | 0 | 3 | 29 | 0 |
| 76 | 1 | 0 | 0 | 0 | 10 | 8 | 17 | 1 | 0 | 8 | 0 | 7 | 48 | 0 |
| 77 | 0 | 1 | 1 | 0 | 5 | 6 | 43 | 0 | 0 | 23 | 0 | 0 | 21 | 0 |
| 78 | 0 | 1 | 0 | 0 | 5 | 10 | 30 | 3 | 0 | 26 | 0 | 0 | 25 | 0 |
| 79 | 2 | 0 | 0 | 0 | 5 | 26 | 36 | 2 | 0 | 18 | 4 | 2 | 5 | 0 |
| 80 | 12 | 0 | 0 | 0 | 4 | 0 | 30 | 4 | 0 | 3 | 28 | 5 | 14 | 0 |
| 81 | 0 | 0 | 3 | 0 | 3 | 3 | 22 | 3 | 0 | 25 | 9 | 5 | 27 | 0 |
| 82 | | | | | | | | | | | | | | |
| 83 | 0 | 1 | 3 | 4 | 6 | 3 | 34 | 2 | 0 | 36 | 3 | 1 | 7 | 0 |
| 84 | 0 | 0 | 3 | 3 | 2 | 5 | 38 | 1 | 0 | 41 | 3 | 1 | 3 | 0 |
| 85 | 0 | 0 | 2 | 1 | 3 | 11 | 24 | 2 | 0 | 30 | 17 | 3 | 7 | 0 |
| 86 | 1 | 0 | 3 | 1 | 4 | 3 | 34 | 2 | 0 | 14 | 23 | 4 | 11 | 0 |
| 87 | 1 | 0 | 0 | 0 | 9 | 4 | 24 | 1 | 0 | 28 | 21 | 4 | 8 | 0 |
| 88 | 1 | 0 | 0 | 0 | 5 | 1 | 13 | 1 | 0 | 14 | 14 | 8 | 43 | 0 |
| 89 | | | | | | | | | | | | | | |
| 90 | 7 | 0 | 5 | 0 | 7 | 5 | 48 | 2 | 0 | 10 | 8 | 3 | 5 | 0 |
| 91 | 1 | 1 | 4 | 2 | 2 | 13 | 42 | 2 | 0 | 14 | 10 | 4 | 5 | 0 |
| 92 | 3 | 0 | 2 | 1 | 2 | 18 | 25 | 2 | 0 | 23 | 15 | 4 | 5 | 0 |
| 93 | 3 | 0 | 3 | 0 | 4 | 1 | 37 | 1 | 0 | 3 | 30 | 7 | 11 | 0 |
| 94 | 0 | 0 | 2 | 0 | 9 | 0 | 25 | 1 | 0 | 3 | 41 | 8 | 11 | 0 |
| 95 | 0 | 0 | 2 | 0 | 2 | 5 | 18 | 1 | 0 | 1 | 50 | 9 | 12 | 0 |
| 96 | 10 | 1 | 1 | 0 | 1 | 0 | 23 | 2 | 0 | 2 | 22 | 22 | 16 | 0 |
| 97 | 18 | 0 | 3 | 0 | 3 | 6 | 37 | 2 | 0 | 7 | 12 | 5 | 7 | 0 |
| 98 | 15 | 0 | 4 | 2 | 4 | 11 | 36 | 1 | 0 | 15 | 7 | 2 | 3 | 0 |
| 99 | 15 | 1 | 0 | 0 | 4 | 11 | 9 | 1 | 0 | 17 | 26 | 7 | 9 | 0 |
| 100 | 1 | 1 | 2 | 0 | 2 | 3 | 28 | 2 | 0 | 4 | 38 | 11 | 8 | 0 |
| 101 | 4 | 0 | 0 | 0 | 2 | 2 | 23 | 2 | 0 | 1 | 42 | 15 | 9 | 0 |
| 102 | 0 | 0 | 3 | 0 | 3 | 3 | 57 | 2 | 0 | 11 | 7 | 1 | 13 | 0 |
| 103 | 0 | 0 | 3 | 0 | 7 | 0 | 34 | 2 | 0 | 38 | 4 | 1 | 11 | 0 |
| 104 | 5 | 0 | 4 | 0 | 2 | 1 | 50 | 2 | 0 | 17 | 6 | 3 | 10 | 0 |
| 105 | 11 | 0 | 4 | 0 | 5 | 0 | 35 | 4 | 0 | 1 | 19 | 19 | 2 | 0 |

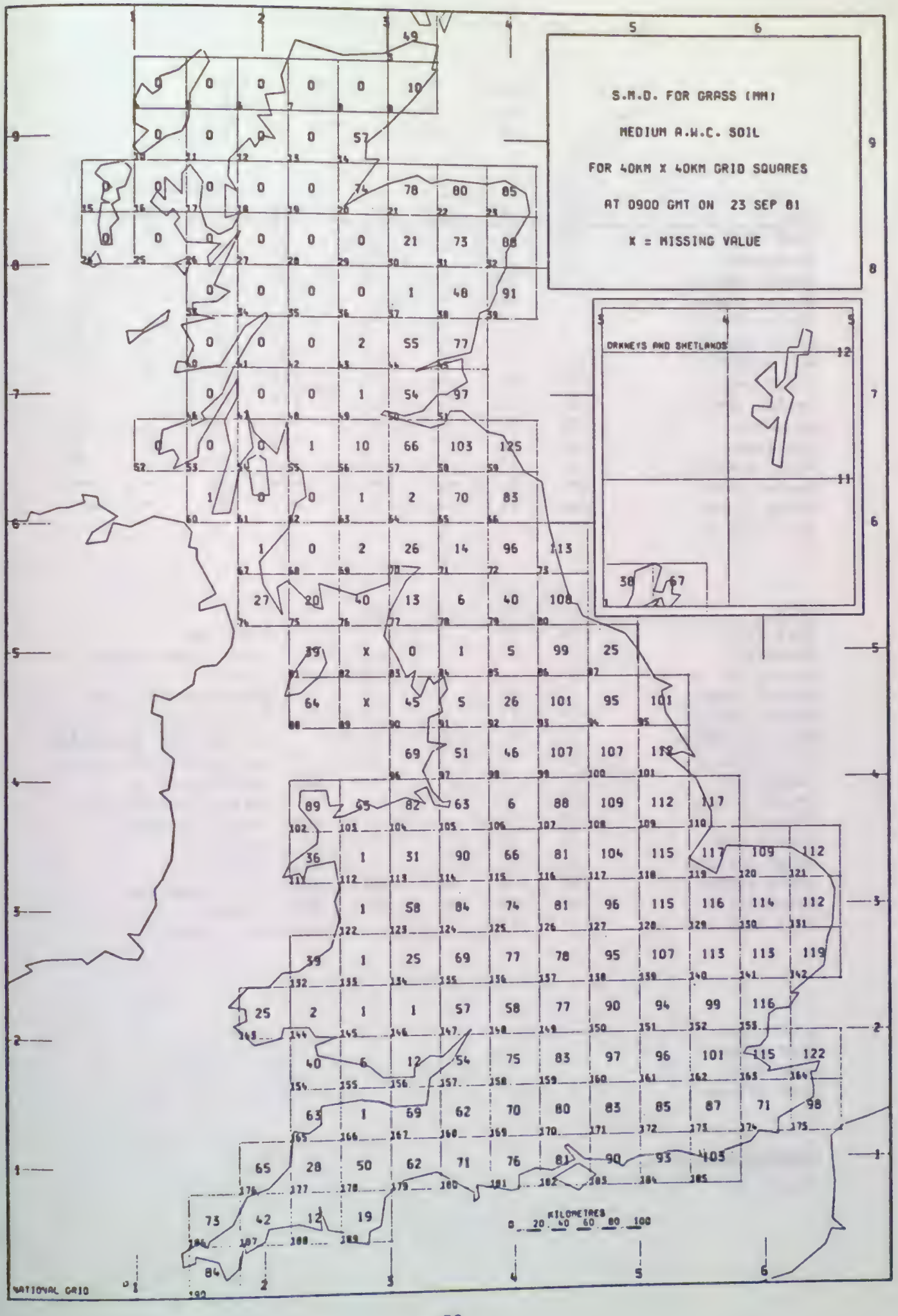
| SQUARE NO. | PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LAND USE (SEE KEY) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 106 | 8 | 0 | 2 | 1 | 2 | 5 | 47 | 3 | 0 | 17 | 8 | 4 | 3 | 0 |
| 107 | 13 | 0 | 2 | 0 | 3 | 1 | 33 | 2 | 0 | 17 | 18 | 4 | 7 | 0 |
| 108 | 1 | 0 | 0 | 0 | 1 | 0 | 30 | 1 | 0 | 4 | 42 | 12 | 9 | 0 |
| 109 | 0 | 0 | 0 | 0 | 4 | 0 | 30 | 1 | 0 | 0 | 43 | 14 | 8 | 0 |
| 110 | 2 | 0 | 0 | 0 | 0 | 0 | 31 | 0 | 0 | 2 | 45 | 9 | 11 | 0 |
| 111 | 0 | 0 | 3 | 0 | 7 | 0 | 37 | 2 | 0 | 40 | 3 | 1 | 7 | 0 |
| 112 | 0 | 1 | 3 | 2 | 10 | 5 | 31 | 2 | 0 | 38 | 2 | 1 | 5 | 0 |
| 113 | 1 | 0 | 3 | 2 | 5 | 2 | 39 | 1 | 0 | 25 | 9 | 2 | 11 | 0 |
| 114 | 1 | 0 | 3 | 0 | 1 | 1 | 47 | 3 | 0 | 6 | 20 | 7 | 11 | 0 |
| 115 | 2 | 0 | 3 | 0 | 3 | 7 | 50 | 2 | 0 | 4 | 16 | 3 | 10 | 0 |
| 116 | 11 | 0 | 3 | 0 | 4 | 1 | 38 | 4 | 0 | 7 | 19 | 4 | 9 | 0 |
| 117 | 1 | 0 | 1 | 0 | 1 | 0 | 31 | 2 | 0 | 2 | 42 | 9 | 11 | 0 |
| 118 | 1 | 0 | 0 | 0 | 2 | 0 | 11 | 1 | 0 | 0 | 52 | 22 | 11 | 0 |
| 119 | 0 | 0 | 7 | 0 | 0 | 0 | 13 | 2 | 0 | 0 | 45 | 23 | 10 | 0 |
| 120 | 0 | 0 | 3 | 0 | 5 | 0 | 5 | 5 | 1 | 0 | 54 | 22 | 5 | 0 |
| 121 | 0 | 0 | 4 | 0 | 1 | 0 | 12 | 3 | 0 | 0 | 53 | 22 | 5 | 0 |
| 122 | 0 | 0 | 2 | 5 | 17 | 0 | 22 | 3 | 0 | 40 | 3 | 1 | 7 | 0 |
| 123 | 0 | 0 | 3 | 1 | 6 | 2 | 47 | 2 | 0 | 15 | 9 | 3 | 12 | 0 |
| 124 | 8 | 0 | 3 | 0 | 2 | 3 | 34 | 2 | 0 | 6 | 22 | 5 | 15 | 0 |
| 125 | 14 | 0 | 3 | 0 | 2 | 2 | 41 | 2 | 0 | 5 | 18 | 3 | 10 | 0 |
| 126 | 9 | 0 | 3 | 0 | 2 | 0 | 46 | 2 | 0 | 3 | 24 | 2 | 9 | 0 |
| 127 | 1 | 0 | 2 | 0 | 1 | 1 | 30 | 3 | 0 | 2 | 47 | 3 | 10 | 0 |
| 128 | 1 | 0 | 2 | 0 | 1 | 1 | 15 | 1 | 0 | 2 | 44 | 28 | 5 | 0 |
| 129 | 0 | 0 | 2 | 0 | 6 | 0 | 11 | 2 | 2 | 0 | 40 | 32 | 5 | 0 |
| 130 | 0 | 0 | 0 | 0 | 10 | 1 | 16 | 2 | 0 | 5 | 43 | 16 | 7 | 0 |
| 131 | 2 | 0 | 2 | 0 | 1 | 2 | 15 | 3 | 1 | 3 | 49 | 18 | 4 | 0 |
| 132 | 0 | 0 | 3 | 1 | 2 | 3 | 44 | 2 | 0 | 24 | 6 | 2 | 13 | 0 |
| 133 | 0 | 0 | 3 | 1 | 6 | 2 | 37 | 3 | 0 | 32 | 4 | 1 | 11 | 0 |
| 134 | 0 | 0 | 3 | 0 | 7 | 0 | 46 | 3 | 2 | 19 | 7 | 0 | 13 | 0 |
| 135 | 1 | 0 | 2 | 0 | 4 | 1 | 40 | 5 | 7 | 4 | 21 | 4 | 11 | 0 |
| 136 | 1 | 0 | 5 | 0 | 1 | 0 | 42 | 3 | 7 | 2 | 37 | 1 | 1 | 0 |
| 137 | 2 | 0 | 3 | 0 | 2 | 5 | 41 | 3 | 0 | 1 | 30 | 3 | 10 | 0 |
| 138 | 2 | 0 | 3 | 0 | 2 | 0 | 35 | 4 | 0 | 0 | 40 | 4 | 10 | 0 |
| 139 | 1 | 0 | 3 | 0 | 0 | 0 | 28 | 2 | 2 | 0 | 44 | 14 | 6 | 0 |

| SQUARE NO. | PERCENTAGES OF LAND USES (1-14) DEVOTED TO EACH SQUARE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LAND USE (SEE KEY) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 140 | 1 | 0 | 3 | 0 | 1 | 0 | 15 | 2 | 2 | 3 | 53 | 15 | 5 | 0 |
| 141 | 1 | 0 | 0 | 0 | 4 | 1 | 16 | 2 | 1 | 2 | 52 | 15 | 6 | 0 |
| 142 | 0 | 0 | 2 | 0 | 4 | 2 | 16 | 4 | 1 | 2 | 50 | 14 | 5 | 0 |
| 143 | 0 | 0 | 3 | 0 | 3 | 2 | 54 | 2 | 0 | 13 | 8 | 3 | 12 | 0 |
| 144 | 1 | 0 | 3 | 0 | 9 | 1 | 52 | 3 | 0 | 14 | 4 | 2 | 11 | 0 |
| 145 | 2 | 0 | 2 | 1 | 10 | 10 | 40 | 2 | 0 | 24 | 2 | 1 | 6 | 0 |
| 146 | 5 | 0 | 3 | 2 | 7 | 5 | 33 | 2 | 0 | 30 | 4 | 2 | 7 | 0 |
| 147 | 4 | 0 | 2 | 0 | 12 | 0 | 38 | 6 | 2 | 0 | 23 | 2 | 11 | 0 |
| 148 | 2 | 0 | 3 | 0 | 5 | 3 | 49 | 4 | 1 | 3 | 20 | 2 | 8 | 0 |
| 149 | 1 | 0 | 3 | 0 | 1 | 2 | 33 | 3 | 0 | 1 | 41 | 3 | 12 | 0 |
| 150 | 1 | 0 | 2 | 0 | 2 | 1 | 45 | 4 | 0 | 1 | 30 | 2 | 12 | 0 |
| 151 | 3 | 0 | 2 | 0 | 3 | 1 | 30 | 4 | 1 | 1 | 41 | 7 | 7 | 0 |
| 152 | 1 | 0 | 2 | 0 | 2 | 0 | 27 | 4 | 1 | 0 | 46 | 11 | 6 | 0 |
| 153 | 2 | 2 | 2 | 0 | 1 | 0 | 26 | 3 | 1 | 0 | 47 | 11 | 5 | 0 |
| 154 | 1 | 0 | 3 | 0 | 8 | 6 | 39 | 2 | 0 | 23 | 5 | 2 | 11 | 0 |
| 155 | 12 | 0 | 0 | 2 | 13 | 7 | 27 | 1 | 0 | 28 | 5 | 0 | 5 | 0 |
| 156 | 13 | 0 | 3 | 1 | 10 | 1 | 47 | 2 | 0 | 9 | 7 | 1 | 6 | 0 |
| 157 | 10 | 0 | 2 | 1 | 3 | 0 | 46 | 4 | 3 | 3 | 16 | 2 | 10 | 0 |
| 158 | 0 | 0 | 3 | 0 | 5 | 0 | 50 | 7 | 0 | 5 | 21 | 1 | 8 | 0 |
| 159 | 0 | 0 | 3 | 0 | 3 | 1 | 26 | 7 | 1 | 6 | 38 | 3 | 12 | 0 |
| 160 | 4 | 0 | 3 | 0 | 8 | 0 | 26 | 8 | 1 | 3 | 33 | 3 | 11 | 0 |
| 161 | 25 | 1 | 4 | 0 | 2 | 0 | 50 | 4 | 2 | 1 | 6 | 2 | 3 | 0 |
| 162 | 19 | 3 | 0 | 0 | 2 | 0 | 23 | 7 | 4 | 0 | 29 | 9 | 4 | 0 |
| 163 | 2 | 0 | 2 | 0 | 2 | 0 | 28 | 7 | 10 | 2 | 30 | 10 | 7 | 0 |
| 164 | 2 | 0 | 2 | 0 | 0 | 0 | 23 | 5 | 5 | 0 | 34 | 22 | 7 | 0 |
| 165. | 0 | 0 | 6 | 0 | 4 | 0 | 54 | 4 | 2 | 10 | 7 | 3 | 10 | 0 |
| 166 | 0 | 0 | 2 | 0 | 4 | 1 | 27 | 4 | 0 | 22 | 17 | 0 | 23 | 0 |
| 167 | 0 | 0 | 4 | 0 | 3 | 1 | 56 | 3 | 1 | 4 | 11 | 2 | 15 | 0 |
| 168 | 0 | 1 | 4 | 1 | 4 | 3 | 49 | 5 | 3 | 4 | 10 | 2 | 14 | 0 |
| 169 | 1 | 0 | 2 | 0 | 2 | 0 | 40 | 4 | 0 | 5 | 33 | 4 | 9 | 0 |
| 170 | 1 | 0 | 2 | 0 | 5 | 1 | 28 | 8 | 0 | 6 | 33 | 3 | 13 | 0 |
| 171 | 3 | 0 | 2 | 0 | 8 | 1 | 27 | 12 | 2 | 8 | 22 | 3 | 12 | 0 |
| 172 | 2 | 0 | 3 | 0 | 6 | 2 | 38 | 13 | 0 | 2 | 18 | 2 | 14 | 0 |
| 173 | 2 | 0 | 3 | 0 | 4 | 0 | 31 | 12 | 11 | 0 | 21 | 3 | 13 | 0 |

| SQUARE NO. | PERCENTAGES OF LAND USES (1-14) DEVOTED TC EACH SQUARE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LAND USE (SEE KEY) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 174 | 1 | 0 | 2 | 0 | 3 | 0 | 34 | 14 | 8 | 0 | 22 | 5 | 11 | 0 |
| 175 | 2 | 0 | 2 | 0 | 2 | 0 | 24 | 8 | 0 | 5 | 34 | 11 | 12 | 0 |
| 176 | 0 | 0 | 5 | 0 | 0 | 0 | 63 | 5 | 0 | 17 | 0 | 5 | 5 | 0 |
| 177 | 0 | 0 | 5 | 0 | 3 | 3 | 62 | 2 | 1 | 7 | 7 | 0 | 10 | 0 |
| 178 | 1 | 0 | 3 | 0 | 5 | 0 | 38 | 6 | 2 | 12 | 13 | 2 | 18 | 0 |
| 179 | 1 | 0 | 5 | 0 | 4 | 0 | 60 | 4 | 2 | 5 | 7 | 1 | 11 | 0 |
| 180 | 0 | 0 | 2 | 0 | 4 | 7 | 35 | 2 | 0 | 6 | 15 | 6 | 23 | 0 |
| 181 | 1 | 0 | 0 | 0 | 4 | 11 | 23 | 3 | 0 | 2 | 36 | 10 | 10 | 0 |
| 182 | 2 | 0 | 1 | 0 | 15 | 0 | 21 | 14 | 0 | 10 | 23 | 4 | 10 | 0 |
| 183 | 7 | 0 | 1 | 0 | 6 | 1 | 18 | 11 | 0 | 8 | 30 | 5 | 13 | 0 |
| 184 | 3 | 0 | 3 | 0 | 2 | 0 | 31 | 6 | 1 | 10 | 25 | 3 | 16 | 0 |
| 185 | 2 | 0 | 2 | 0 | 4 | 0 | 40 | 8 | 1 | 8 | 18 | 2 | 15 | 0 |
| 186 | 2 | 0 | 4 | 6 | 2 | 1 | 45 | 10 | 0 | 10 | 0 | 10 | 10 | 0 |
| 187 | 1 | 0 | 4 | 6 | 2 | 2 | 54 | 4 | 0 | 5 | 0 | 11 | 11 | 0 |
| 188 | 2 | 3 | 4 | 0 | 3 | 4 | 56 | 3 | 0 | 10 | 0 | 8 | 7 | 0 |
| 189 | 2 | 0 | 3 | 0 | 3 | 0 | 30 | 5 | 0 | 18 | 15 | 0 | 24 | 0 |
| 190 | 2 | 0 | 3 | 0 | 0 | 0 | 44 | 6 | 0 | 20 | 0 | 17 | 8 | 0 |

PE's for impervious urban land use are calculated using a maximum available daily moisture of 0.5 mm. AE is set equal to PE when R $\geq$ PE, or to R (R < PE). Run-off for bare rock is assumed to be so rapid that PE is ignored (with AE=0), so that HER = rainfall.

## Annexe C Examples of MORECS outputs


S.M.D. FOR GRASS (MM)
MEDIUM A.W.C. SOIL
FOR 40KM X 40KM GRID SQUARES
AT 0900 GMT ON 23 SEP 81
X = MISSING VALUE
ORKNEYS AND SHETLANDS
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

MORECS DATA FOR SQUARE 172 WEEK ENDING 8.9.81

| Total Rain | Total Sun | Mean Temp | Mean Wind | Mean V.P. |
|---|---|---|---|---|
| 0.0 | 48 | 14.7 | 84 | 12.6 |

| | HIGH AWC | | | | MEDIUM AWC | | | |
|---|---|---|---|---|---|---|---|---|
| CROP | SMD | PE | AE | HER | SMD | PE | AE | HER |
| Bare soil | 25 | 14 | 0 | 0 | 20 | 12 | 0 | 0 |
| Grassland | 142 | 16 | 8 | 0 | 122 | 16 | 2 | 0 |
| Spring barley | 76 | 14 | 0 | 0 | 65 | 12 | 0 | 0 |
| Winter wheat | 76 | 14 | 0 | 0 | 65 | 12 | 0 | 0 |
| Winter barley | 38 | 14 | 0 | 0 | 27 | 12 | 0 | 0 |
| Early potatoes | 34 | 14 | 0 | 0 | 22 | 12 | 0 | 0 |
| M/C potatoes | 105 | 14 | 1 | 0 | 86 | 12 | 0 | 0 |
| Sugar beet | 132 | 17 | 10 | 0 | 120 | 17 | 8 | 0 |
| Decid. trees | 127 | 16 | 10 | 0 | 116 | 16 | 8 | 0 |
| Orchards | 112 | 15 | 9 | 0 | 103 | 15 | 8 | 0 |
| Coniferous | 124 | 16 | 9 | 0 | 113 | 16 | 7 | 0 |
| Rough grazing | 43 | 13 | 6 | 0 | 39 | 13 | 5 | 0 |
| Spare spare | *** | ** | ** | *** | *** | ** | ** | *** |
| Spare spare | *** | ** | ** | *** | *** | ** | ** | *** |
| Real land use | 113 | 15 | 7 | 0 | 98 | 15 | 3 | 0 |

| | LOW AWC | | | |
|---|---|---|---|---|
| CROP | SMD | PE | AE | HER |
| Bare soil | 15 | 11 | 0 | 0 |
| Grassland | 92 | 16 | 1 | 0 |
| Spring barley | 50 | 11 | 0 | 0 |
| Winter wheat | 50 | 11 | 0 | 0 |
| Winter barley | 15 | 11 | 0 | 0 |
| Early potatoes | 15 | 11 | 0 | 0 |
| M/C potatoes | 63 | 11 | 0 | 0 |
| Sugar beet | 100 | 17 | 6 | 0 |
| Decid. trees | 102 | 16 | 7 | 0 |
| Orchards | 88 | 15 | 6 | 0 |
| Coniferous | 99 | 16 | 6 | 0 |
| Rough grazing | 34 | 13 | 4 | 0 |
| Spare spare | *** | ** | ** | *** |
| Spare spare | *** | ** | ** | *** |
| Real land use | 77 | 15 | 2 | 0 |

KEY

PE – Potential evapotranspiration

AE – Actual evapotranspiration

SMD– Soil moisture deficit at 0900 hrs Wednesday week ending as above

HER– Hydrologically effective rainfall

AWC– Available water capacity

RAIN– (MM)

WIND– Miles per day

SUN – Hours

V.P.– Millibars

Your name
Your farm
Your town
Your county
Postcode

Crown Copyright 1981

MORECS DATA FOR WEEK ENDING 22 9 81

UNITS SUN,HRS WIND,MILES PER DAY TEMP,DEG C VP,MBARS ***,NO CROP GROWN SOIL,MEDIUM A.W.C.

| | BARE SOIL | | | GRASS | | | SP.BARLEY | | | WIN.WHEAT | | | M/C POTATO | | | SUGAR BEET | | | ORCHARDS | | | TOT | TOT | MEAN | MEAN | MEAN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SQ | SMD | PE | AE | SMD | PE | AE | SMD | PE | AE | SMD | PE | AE | SMD | PE | AE | SMD | PE | AE | SMD | PE | AE | RAIN | SUN | WIND | TEMP | VP |
| 71 | 0 | 9 | 9 | 14 | 15 | 15 | 0 | 9 | 9 | 0 | 9 | 9 | 12 | 17 | 17 | *** | ** | ** | *** | ** | ** | 46 | 31 | 254 | 12.2 | 11.9 |
| 72 | 3 | 10 | 10 | 96 | 16 | 16 | 56 | 10 | 10 | 58 | 10 | 10 | 66 | 18 | 18 | *** | ** | ** | 67 | 16 | 16 | 25 | 32 | 272 | 12.8 | 11.8 |
| 73 | 5 | 11 | 11 | 113 | 18 | 17 | 88 | 11 | 11 | 90 | 11 | 11 | 70 | 11 | 11 | 115 | 19 | 18 | 98 | 17 | 16 | 19 | 39 | 319 | 13.6 | 11.9 |
| 74 | 2 | 10 | 10 | 27 | 16 | 16 | 2 | 10 | 10 | 1 | 11 | 11 | 2 | 10 | 10 | *** | ** | ** | 4 | 16 | 16 | 45 | 33 | 404 | 13.1 | 12.9 |
| 75 | 4 | 9 | 9 | 20 | 15 | 15 | 4 | 9 | 9 | 2 | 10 | 10 | 4 | 9 | 9 | *** | ** | ** | 5 | 15 | 15 | 50 | 36 | 336 | 12.9 | 12.8 |
| 76 | 3 | 10 | 10 | 40 | 16 | 16 | 3 | 10 | 10 | 15 | 12 | 12 | 12 | 10 | 10 | *** | ** | ** | 17 | 16 | 16 | 48 | 36 | 300 | 12.8 | 12.5 |
| 77 | 1 | 10 | 10 | 13 | 15 | 15 | 1 | 10 | 10 | 1 | 10 | 10 | 8 | 10 | 10 | *** | ** | ** | 3 | 16 | 16 | 23 | 36 | 261 | 12.9 | 12.4 |
| 78 | 0 | 9 | 9 | 6 | 16 | 16 | 0 | 9 | 9 | 0 | 11 | 11 | 6 | 18 | 17 | *** | ** | ** | *** | ** | ** | 46 | 32 | 265 | 12.0 | 11.7 |
| 79 | 1 | 9 | 9 | 40 | 16 | 16 | 3 | 9 | 9 | 10 | 11 | 11 | 26 | 18 | 18 | *** | ** | ** | *** | ** | ** | 34 | 33 | 276 | 12.0 | 11.4 |
| 80 | 5 | 11 | 11 | 107 | 17 | 17 | 80 | 11 | 11 | 84 | 11 | 11 | 63 | 11 | 11 | 104 | 18 | 18 | 90 | 17 | 16 | 22 | 39 | 302 | 13.4 | 11.9 |
| 81 | 4 | 10 | 10 | 39 | 15 | 15 | 4 | 10 | 10 | 4 | 10 | 10 | 14 | 10 | 10 | *** | ** | ** | 8 | 15 | 15 | 43 | 40 | 344 | 12.8 | 12.5 |
| 82 | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | *** | **** | **** |
| 83 | 0 | 10 | 10 | 0 | 16 | 16 | 0 | 10 | 10 | 0 | 10 | 10 | 0 | 10 | 10 | *** | ** | ** | *** | ** | ** | 77 | 31 | 283 | 12.5 | 12.0 |
| 84 | 0 | 9 | 9 | 1 | 16 | 16 | 0 | 9 | 9 | 0 | 9 | 9 | 2 | 18 | 18 | *** | ** | ** | *** | ** | ** | 61 | 28 | 294 | 12.1 | 11.7 |
| 85 | 2 | 10 | 10 | 5 | 15 | 15 | 2 | 10 | 10 | 2 | 10 | 10 | 6 | 17 | 17 | *** | ** | ** | *** | ** | ** | 44 | 31 | 295 | 11.8 | 11.3 |
| 86 | 5 | 11 | 11 | 98 | 17 | 16 | 58 | 11 | 11 | 71 | 11 | 11 | 54 | 11 | 11 | 95 | 18 | 17 | 83 | 16 | 16 | 26 | 37 | 296 | 13.1 | 11.8 |
| 87 | 4 | 10 | 10 | 25 | 16 | 16 | 4 | 10 | 10 | 4 | 10 | 10 | 10 | 10 | 10 | 26 | 17 | 17 | *** | ** | ** | 39 | 38 | 322 | 12.7 | 12.1 |
| 88 | 4 | 10 | 10 | 64 | 16 | 16 | 7 | 10 | 10 | 17 | 10 | 10 | 35 | 10 | 10 | *** | ** | ** | 35 | 16 | 16 | 39 | 40 | 335 | 13.1 | 12.6 |
| 89 | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | ** | *** | ** | *** | **** | **** |
| 90 | 3 | 11 | 11 | 44 | 18 | 18 | 3 | 11 | 11 | 3 | 11 | 11 | 27 | 11 | 11 | *** | ** | ** | 18 | 18 | 18 | 38 | 37 | 329 | 13.7 | 12.8 |
| 91 | 2 | 10 | 10 | 5 | 16 | 16 | 2 | 10 | 10 | 2 | 10 | 10 | 6 | 19 | 19 | *** | ** | ** | 4 | 17 | 17 | 48 | 30 | 315 | 13.0 | 12.1 |
| 92 | 2 | 10 | 10 | 26 | 16 | 16 | 2 | 10 | 10 | 2 | 10 | 10 | 9 | 18 | 18 | *** | ** | ** | *** | ** | ** | 46 | 29 | 313 | 12.2 | 11.5 |
| 93 | 4 | 11 | 11 | 101 | 17 | 16 | 50 | 11 | 11 | 66 | 11 | 11 | 62 | 11 | 11 | 98 | 18 | 17 | 82 | 16 | 15 | 27 | 34 | 309 | 13.3 | 12.1 |
| 94 | 4 | 11 | 11 | 95 | 17 | 16 | 36 | 11 | 11 | 50 | 11 | 11 | 49 | 11 | 11 | 79 | 18 | 17 | 63 | 16 | 16 | 30 | 34 | 329 | 13.5 | 12.4 |
| 95 | 5 | 11 | 11 | 101 | 17 | 16 | 53 | 11 | 11 | 65 | 11 | 11 | 56 | 11 | 11 | 93 | 18 | 17 | 77 | 16 | 16 | 27 | 34 | 328 | 13.6 | 12.5 |
| 96 | 3 | 11 | 11 | 69 | 18 | 17 | 3 | 11 | 11 | 7 | 11 | 11 | 47 | 11 | 11 | 64 | 18 | 18 | 38 | 17 | 17 | 31 | 37 | 306 | 14.1 | 13.4 |
| 97 | 2 | 11 | 11 | 51 | 17 | 17 | 2 | 11 | 11 | 2 | 11 | 11 | 34 | 11 | 11 | 49 | 18 | 18 | 26 | 18 | 17 | 39 | 33 | 312 | 13.6 | 12.5 |
| 98 | 2 | 10 | 10 | 46 | 15 | 15 | 2 | 10 | 10 | 2 | 10 | 10 | 25 | 17 | 17 | 40 | 16 | 16 | *** | ** | ** | 41 | 29 | 329 | 12.2 | 11.7 |
| 99 | 4 | 11 | 11 | 106 | 16 | 16 | 54 | 11 | 11 | 74 | 11 | 11 | 67 | 11 | 11 | 111 | 17 | 17 | 94 | 16 | 15 | 24 | 31 | 306 | 13.5 | 12.4 |
| 100 | 4 | 11 | 11 | 107 | 16 | 16 | 61 | 11 | 11 | 62 | 11 | 11 | 60 | 11 | 11 | 114 | 17 | 17 | 97 | 16 | 16 | 22 | 32 | 295 | 14.0 | 12.9 |
| 101 | 5 | 11 | 11 | 112 | 17 | 17 | 76 | 11 | 11 | 81 | 11 | 11 | 65 | 11 | 11 | 122 | 19 | 18 | 107 | 17 | 16 | 22 | 33 | 353 | 14.1 | 12.9 |
| 102 | 2 | 11 | 11 | 89 | 20 | 20 | 38 | 11 | 11 | 44 | 11 | 11 | 43 | 11 | 11 | 81 | 20 | 20 | 58 | 19 | 19 | 42 | 44 | 427 | 14.1 | 13.3 |
| 103 | 1 | 9 | 9 | 45 | 16 | 15 | 1 | 9 | 9 | 1 | 9 | 9 | 21 | 9 | 9 | 40 | 16 | 16 | 20 | 16 | 16 | 44 | 36 | 315 | 12.8 | 13.0 |
| 104 | 1 | 10 | 10 | 82 | 15 | 15 | 32 | 10 | 10 | 32 | 10 | 10 | 50 | 10 | 10 | 73 | 15 | 15 | 56 | 15 | 15 | 32 | 35 | 269 | 13.0 | 13.2 |
| 105 | 1 | 10 | 10 | 63 | 15 | 15 | 1 | 10 | 10 | 2 | 10 | 10 | 29 | 10 | 10 | 55 | 16 | 16 | 36 | 15 | 15 | 30 | 31 | 275 | 13.0 | 12.6 |

## Annexe D Comparison of MORECS and neutron probe data

The following 10 diagrams show comparisons between MORECS estimates of soil moisture deficit and values deduced from neutron probe measurements.

Certain qualifications of the meteorological data which were used, and of certain of the probe data, are required:

(i) Case 4 (Table 4.6.1): the initial SMD (neutron probe) was assumed to be 33 mm (P E Francis, personal communication)

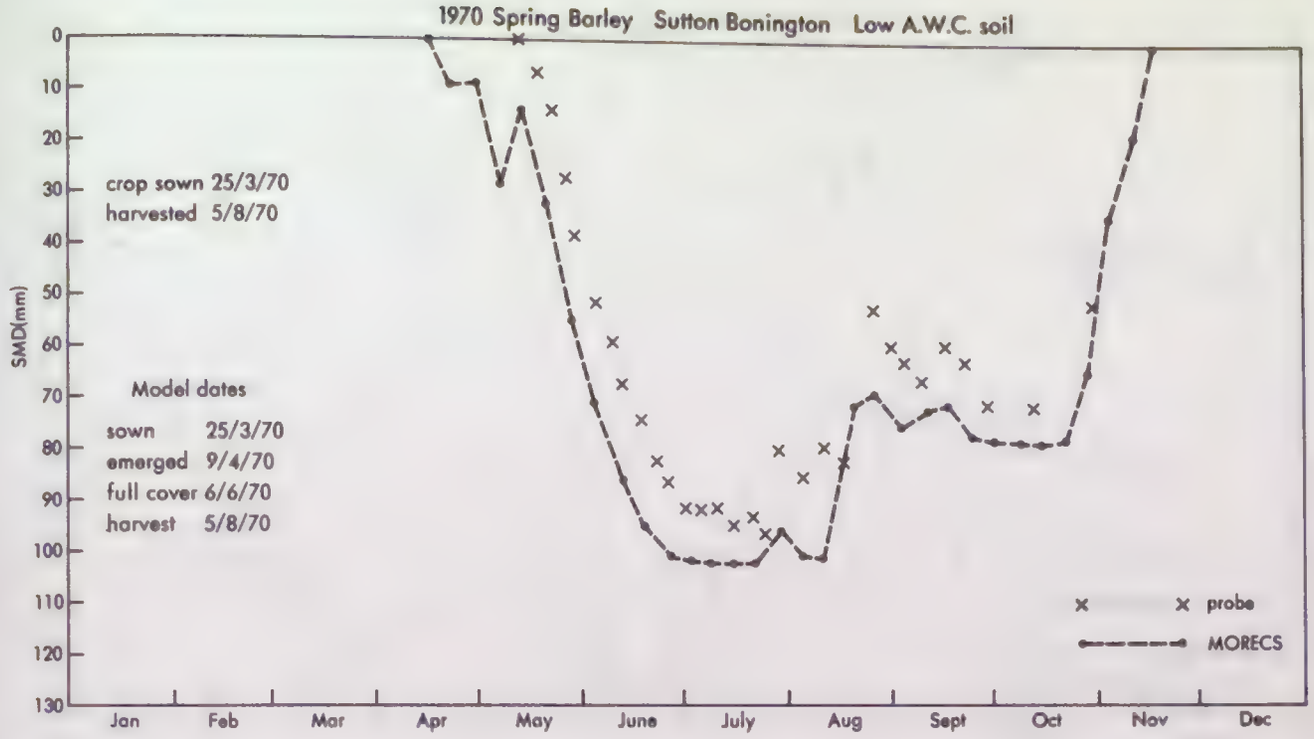
(ii) Cases 5 and 8: Broom's Barn has a very high available water content: it has been set equal to 210 mm here

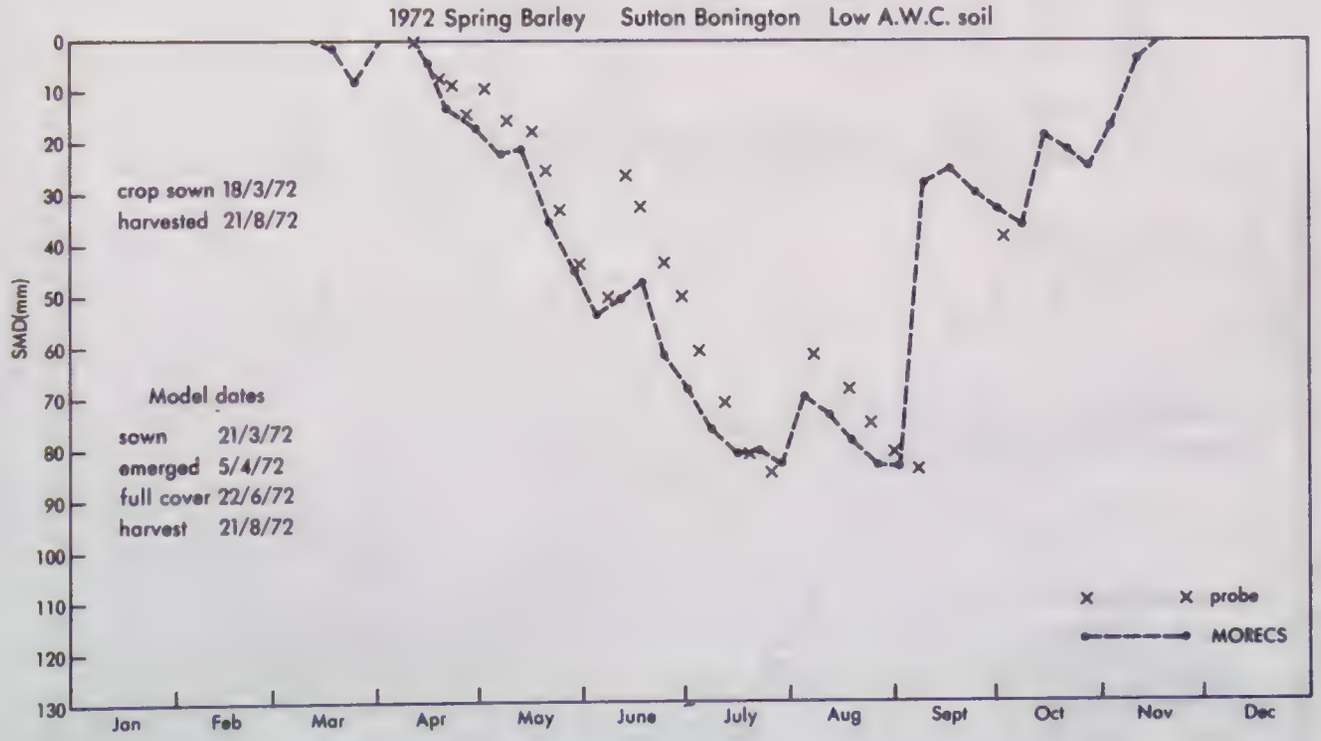
(iii) Case 6: The meteorological data were from Long Ashton. Filton rainfall was taken for 4-17 June, 28 June and 16 August - 1st September

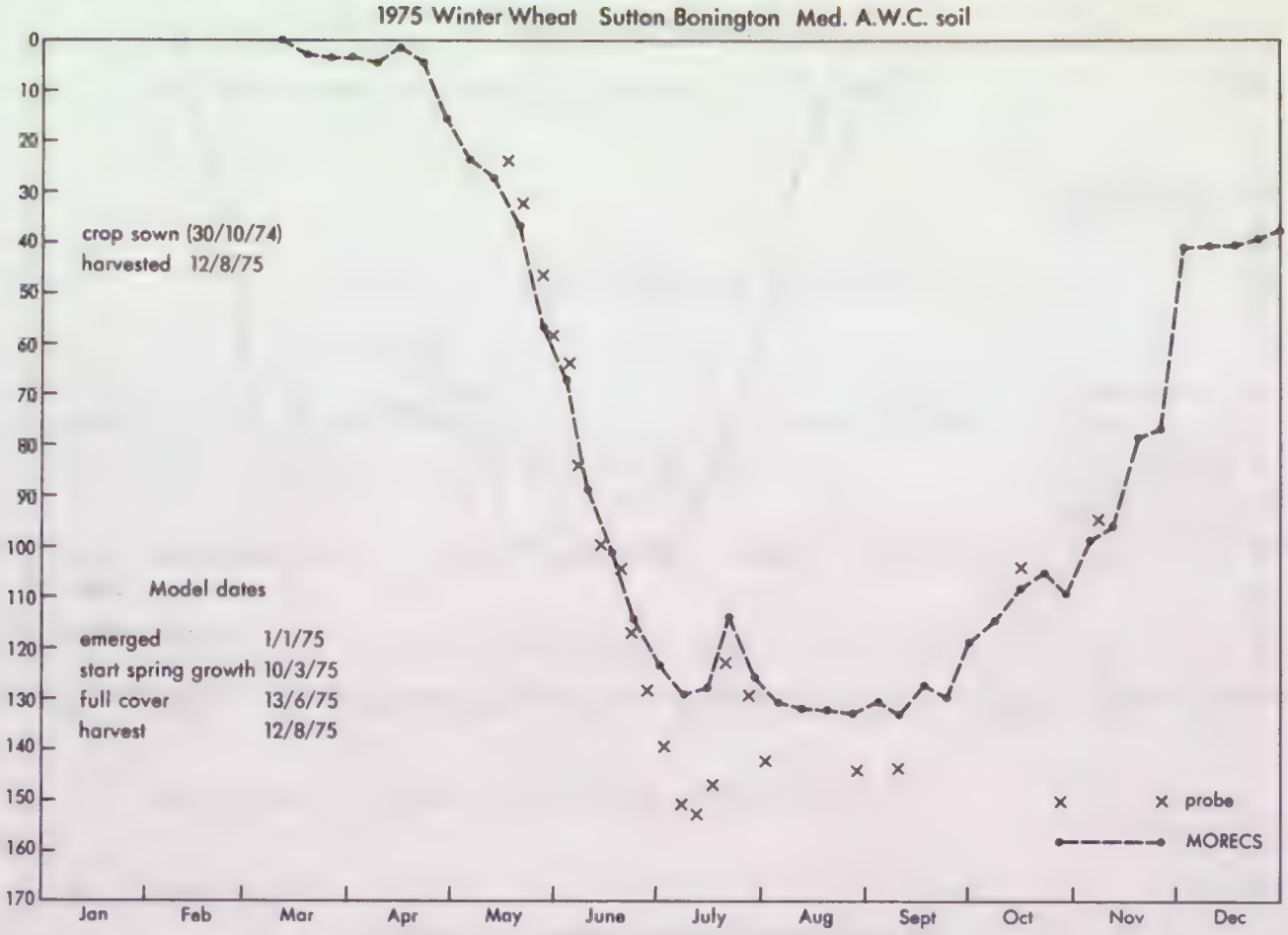
(iv) Case 7: The probe site was 30 km southeast of Finningley. References to rainfall stations nearer the probe site suggested that significant adjustments were required to the Finningley rainfall on several days:

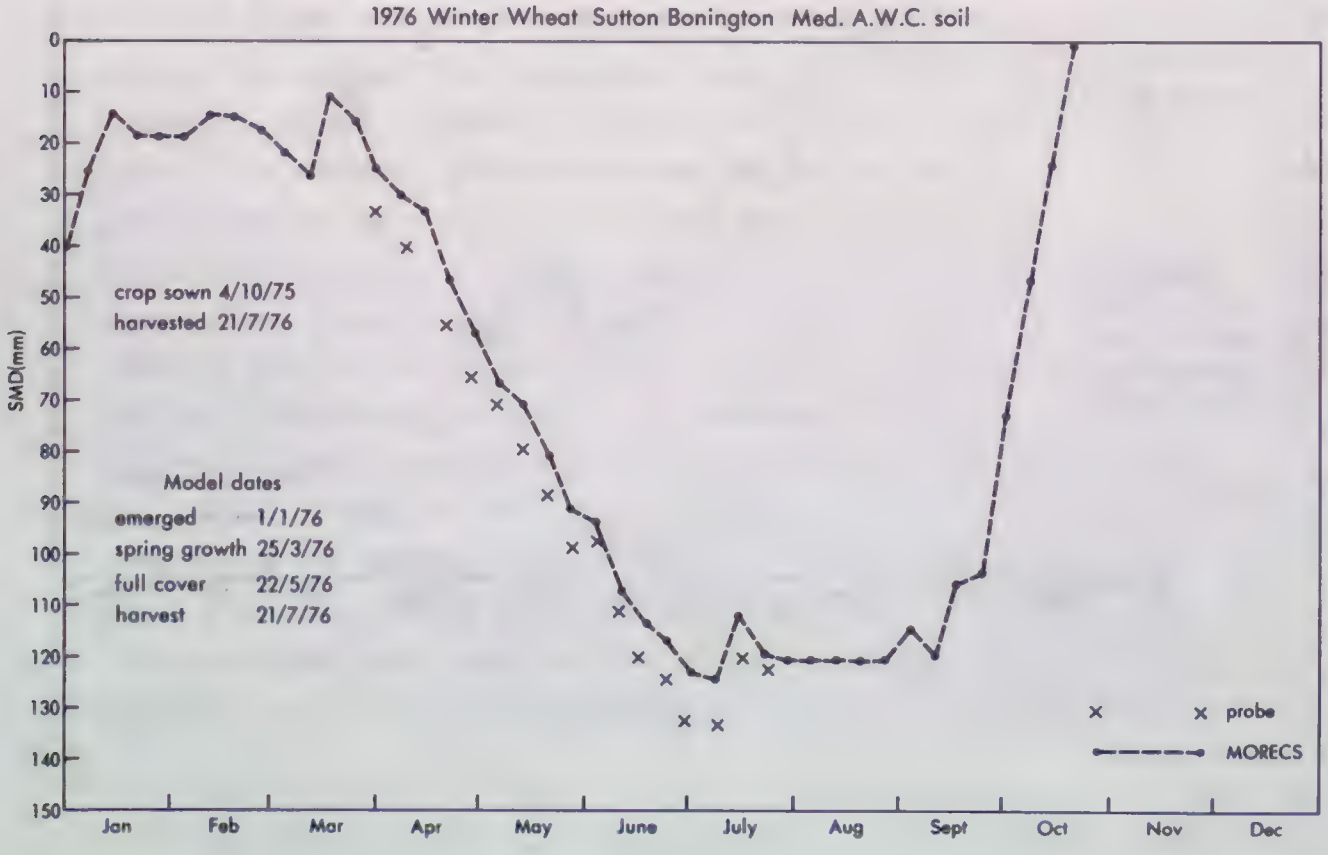
| Date | Finningley rainfall (mm) | Estimated MORECS rainfall (mm) |
|---|---|---|
| 15 June | 12.2 | 6 |
| 16 June | 8.9 | 4 |
| 1 July | 2.8 | 6 |
| 22 July | 2.3 | 5 |

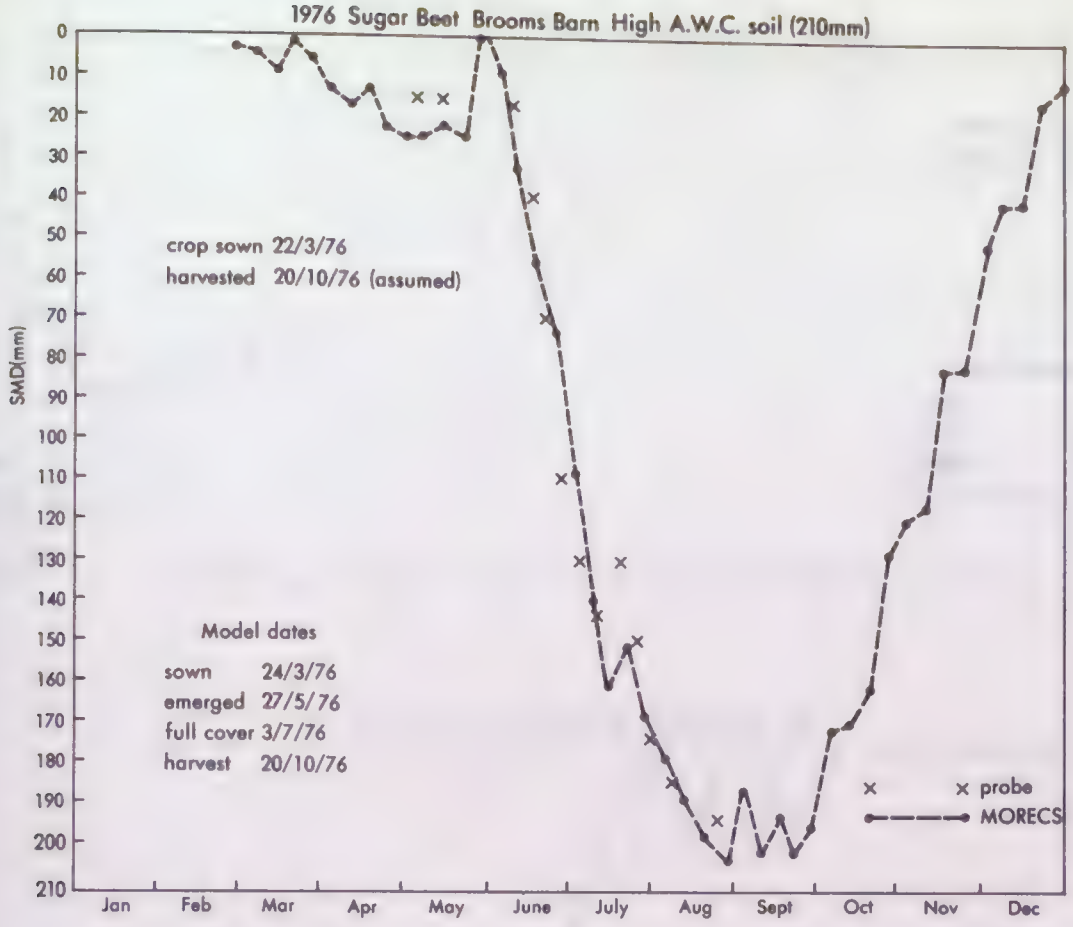
(v) Case 10: SMD was reset from 12 mm to 0 mm on 12 June.

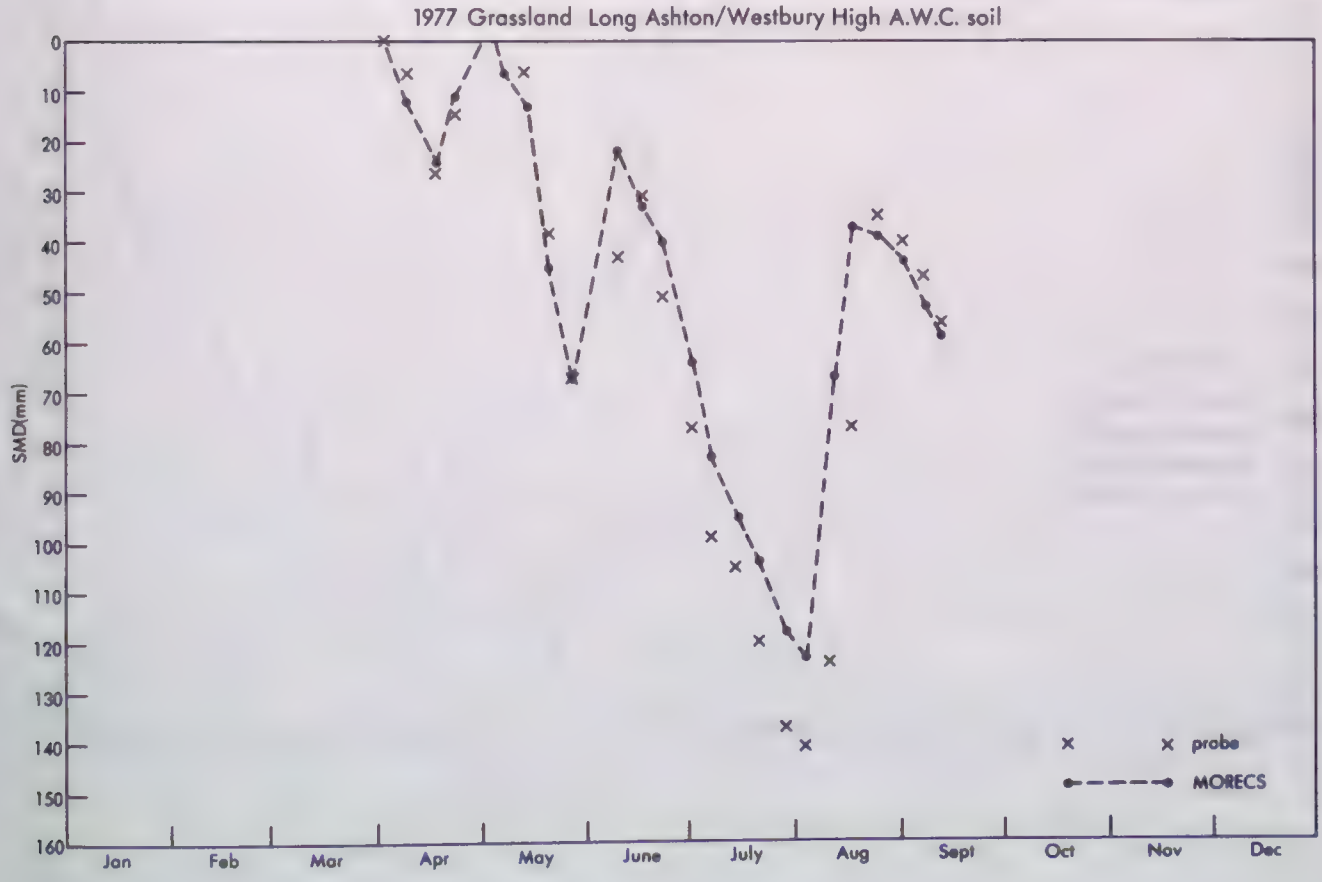

1970 Spring Barley Sutton Bonington Low A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
crop sown 25/3/70
harvested 5/8/70
Model dates
sown 25/3/70
emerged 9/4/70
full cover 6/6/70
harvest 5/8/70
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

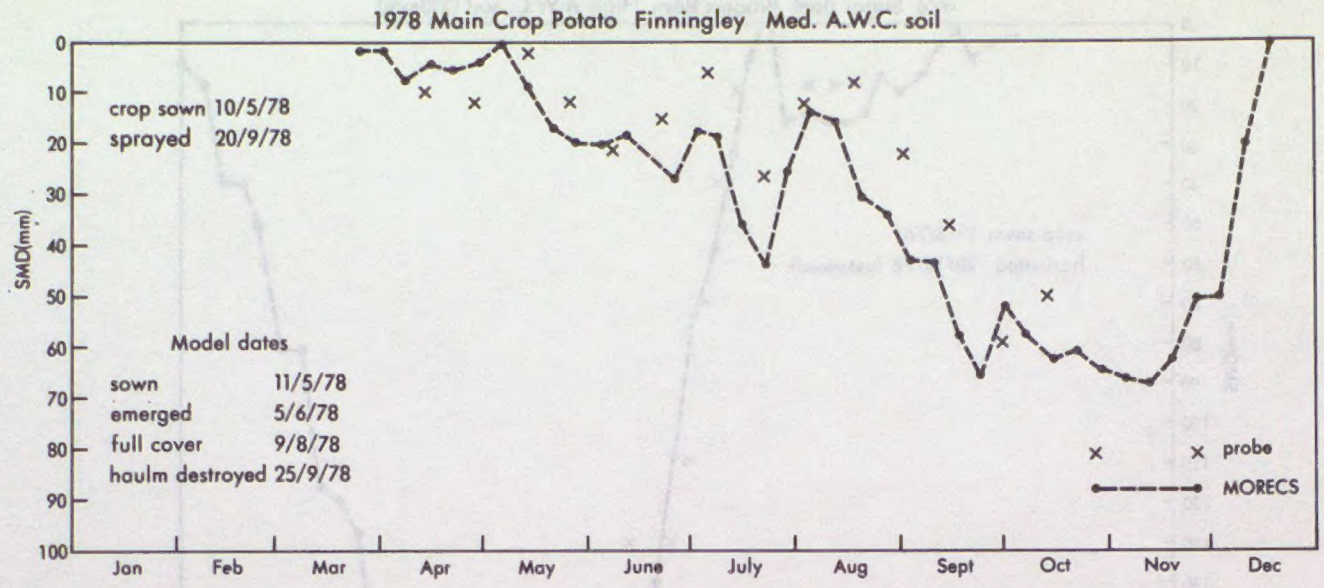

1972 Spring Barley Sutton Bonington Low A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
crop sown 18/3/72
harvested 21/8/72
Model dates
sown 21/3/72
emerged 5/4/72
full cover 22/6/72
harvest 21/8/72
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

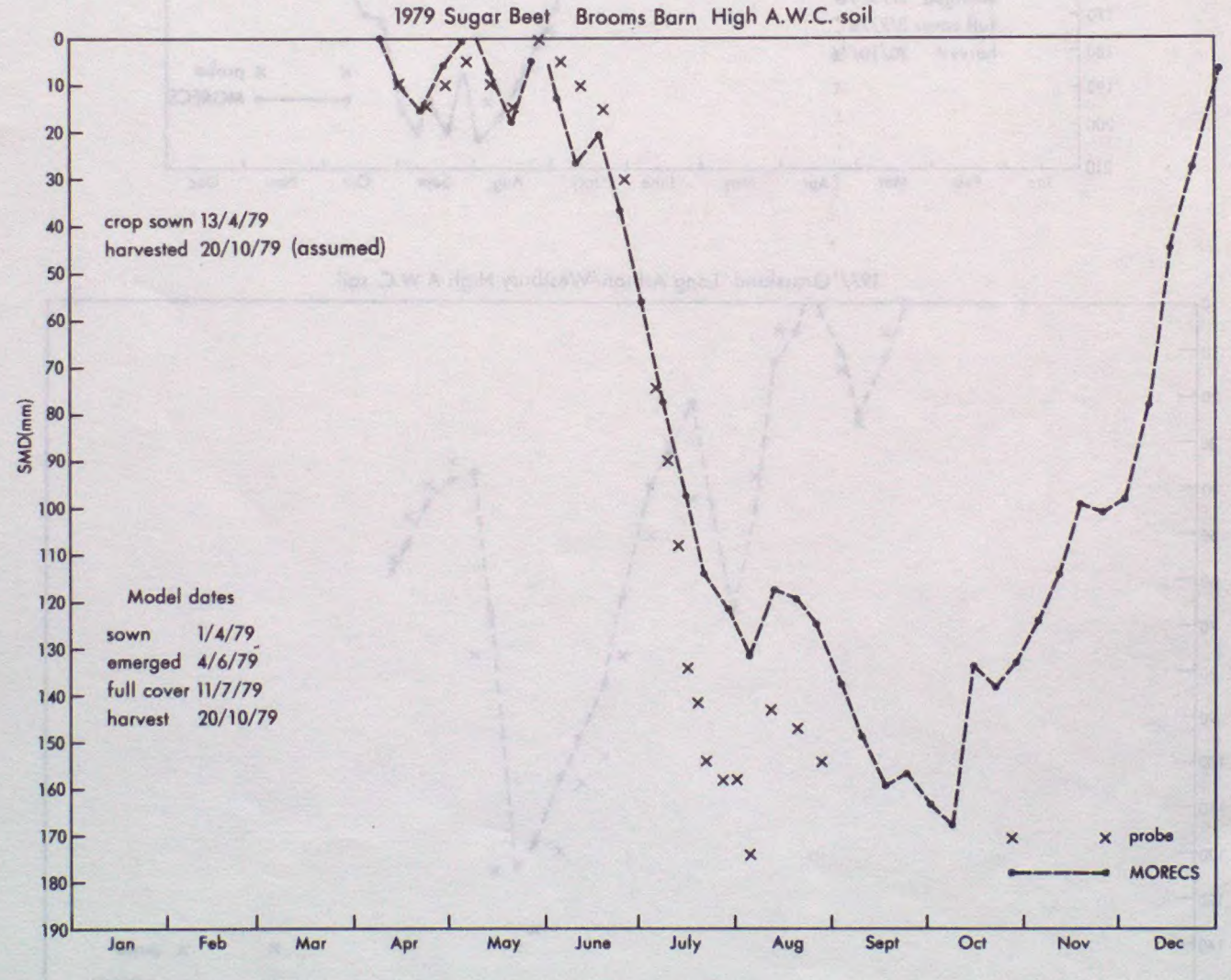

1975 Winter Wheat Sutton Bonington Med. A.W.C. soil
crop sown (30/10/74)
harvested 12/8/75
Model dates
emerged 1/1/75
start spring growth 10/3/75
full cover 13/6/75
harvest 12/8/75
probe
MORECS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1976 Winter Wheat Sutton Bonington Med. A.W.C. soil
SMD(mm)
crop sown 4/10/75
harvested 21/7/76
Model dates
emerged 1/1/76
spring growth 25/3/76
full cover 22/5/76
harvest 21/7/76
probe
MORECS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

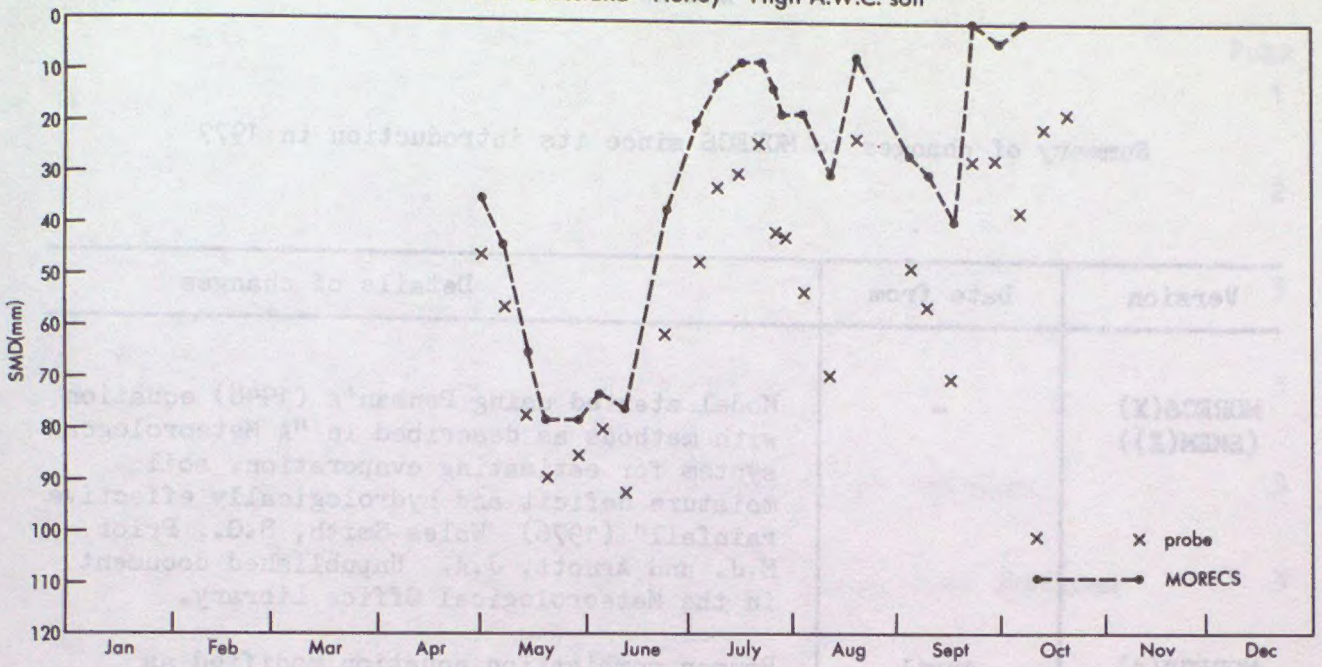

1976 Sugar Beet Brooms Barn High A.W.C. soil (210mm)
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
crop sown 22/3/76
harvested 20/10/76 (assumed)
Model dates
sown 24/3/76
emerged 27/5/76
full cover 3/7/76
harvest 20/10/76
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1977 Grassland Long Ashton/Westbury High A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

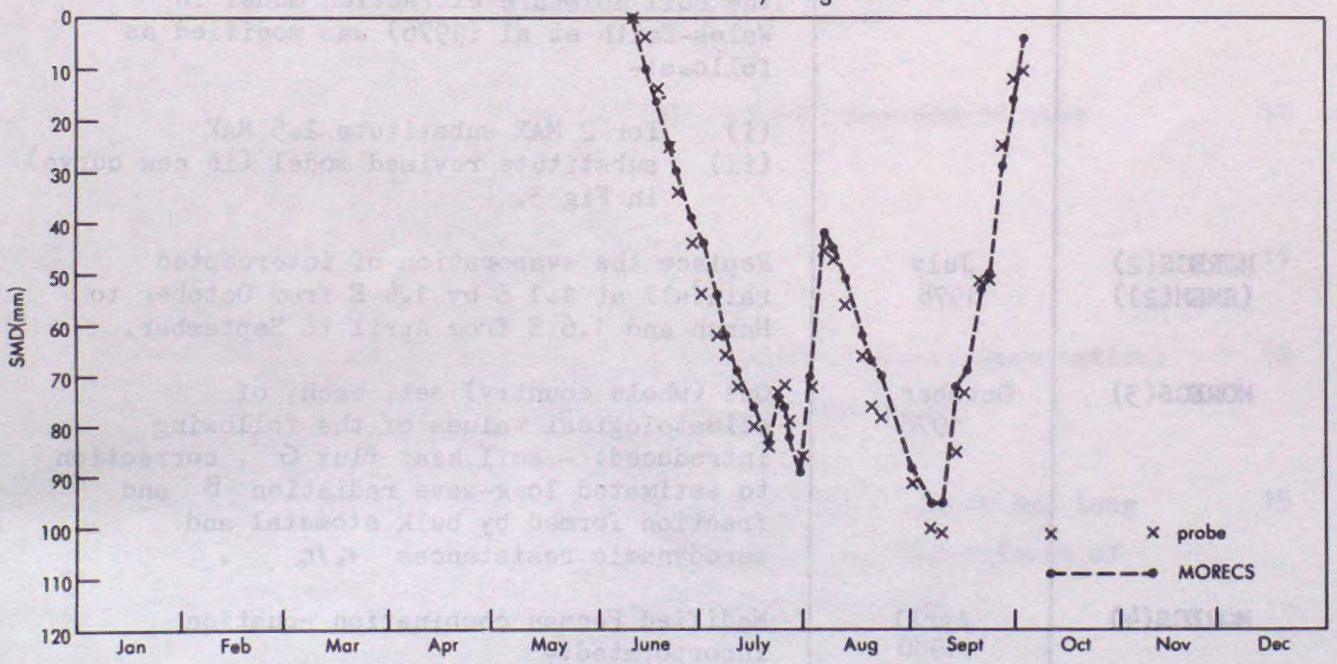

1978 Main Crop Potato Finningley Med. A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
crop sown 10/5/78
sprayed 20/9/78
Model dates
sown 11/5/78
emerged 5/6/78
full cover 9/8/78
haulm destroyed 25/9/78
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec


1979 Sugar Beet Brooms Barn High A.W.C. soil
SMD(mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
crop sown 13/4/79
harvested 20/10/79 (assumed)
Model dates
sown 1/4/79
emerged 4/6/79
full cover 11/7/79
harvest 20/10/79
probe
MORECS
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

1980 Grassland Hurley High A.W.C. soil




1981 Grassland Hurley High AWC soil



Annexe E

## Summary of changes to MORECS since its introduction in 1977

| Version | Date from | Details of changes |
|---|---|---|
| MORECS(X) (SMEM(X)) | - | Model started using Penman's (1948) equation with methods as described in "A Meteorologcal system for estimating evaporation, soil moisture deficit and hydrologically effective rainfall" (1976) Wales-Smith, B.G., Prior M.J. and Arnott, J.A. Unpublished document in the Meteorological Office Library. |
| MORECS(1) (SMEM(1)) | April 1978 | Penman combination equation modified as follows:- for $\frac{\Delta}{\Delta+\gamma}$ and $\frac{\gamma}{\Delta+\gamma}$ substitute $\frac{\Delta}{\Delta+2.4\gamma}$ and $\frac{2.5\gamma}{\Delta+2.4\gamma}$ and for $a+bn/N$ substitute $\delta(a+bn/N)+(1-\delta)c$<br><br>The soil moisture extraction model in Wales-Smith et al (1976) was modified as follows:-<br><br>(i) for 2 MAX substitute 2.5 MAX<br>(ii) substitute revised model (ie new curve) in Fig 3. |
| MORECS(2) (SMEM(2)) | July 1978 | Replace the evaporation of intercepted rainfall at 1.1 E by 1.4 E from October to March and 1.6 E from April to September. |
| MORECS(3) | October 1978 | One (whole country) set, each, of climatological values of the following introduced: - soil heat flux G , correction to estimated long-wave radiation B and fraction formed by bulk stomatal and aerodynamic resistances $r_s/r_a$ . |
| MORECS(4) | April 1980 | Modified Penman combination equation incorporated:-<br>$E_t = \frac{\Delta(R_N-G)+0.17\times2.5\,(1+0.54U)(e_s-e)}{\Delta+\gamma\,(1+2.5r_s(1+0.54U)/250)}$ |
| MORECS(5) | April 1981 | Revised (larger) values of $r_s$ introduced. |
| MORECS(6) | May 1981 | Whole MORECS system revised. Write-up of the new system produced in July 1981 |

| Version | Date from | Details of changes |
|---|---|---|
| MORECS (7) | March 1982 | Revised surface resistance and leaf area index values for grass land.<br>Amended crop development dates for areas in Wales and the South West (figs. A1 to A6) |